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AIRCRAFT EQUIPMENT DIVISION

NASA CR-
160734

REPORT

SOLID POLYMER ELECTROLYTE
FUEL CELL TECHNOLOGY PROGRAM

FINAL REPORT (PHASE V)

Contract NAS 9-15286, DRL Line Item No. 4

Prepared for

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas 77058

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GENERAL ELECTRIC

ACKNOWLEDGEMENTS

This report summarizes the results of the solid polymer electrolyte Fuel Cell Technology Program conducted for the National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, Texas, by the General Electric Company, Direct Energy Conversion Programs, Wilmington, Massachusetts, under Contract NAS 9-15286. The period of performance was February, 1979 through March, 1980.

This work was performed under the guidance of Mr. G. D. Hydrick, Jr., Program Manager for the Power and Propulsion Branch of NASA/Lyndon B. Johnson Space Center. The overall program was directed by J. F. McElroy, Project Engineer, General Electric Company, Direct Energy Conversion Programs.

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1.0 SUMMARY

The overall objectives of Phase V of the SPE Fuel Cell Technology Development Program were to:

- Establish SPE fuel cell life and performance at temperatures, pressures and current densities significantly higher than those previously demonstrated in sub-scale hardware.
- Continued operation of single-cell (1.1 ft^2) Buildup No. 1 to establish life capabilities of the full-scale hardware.
- To design, fabricate and test-evaluate a multi-cell full-scale unit (Buildup No. 2), laying the groundwork for the construction of a reactor stack.
- Design, fabricate and test-evaluate a reactor stack to demonstrate the readiness of SPE fuel cell technology for future space applications.

During this phase, significant progress was made toward the accomplishment of these objectives. In the area of sub-scale fuel cell life, for instance, the 0.7 ft^2 cell stack demonstrated over 11,000 hours of operation at intermediate current densities, temperatures, and low pressures. A 0.05 ft^2, laboratory-size cell demonstrated over 4300 hours of stable life at high pressure and high current density. Both of these cells utilized the conductive cathode wetproofing, a configuration which provides significant performance and weight benefits when scaled to large-size cells.

Buildup No. 1 accumulated over 3200 hours of invariant performance over the current density range between 100 and 500 ASF. The unit ultimately shut down due to failure of a facility-associated oxygen solenoid valve. All testing was performed utilizing commercial-grade reactants. A teardown analysis of Buildup No. 1 revealed no evidence of materials degradation.

Buildup No. 2 featured the same basic design as Buildup No. 1, only in a 4-cell configuration. Minor modifications were incorporated into the end plate, the oxygen flow field, and the coolant cartridge frame. The design modifications all resulted in an improved condition for Buildup No. 2. During the over

1000 hours of Buildup No. 2 operation, several design and fabrication shortcomings were identified and corrective actions subsequently implemented.

The lessons learned and corrective measures taken during operation of B/U Nos. 1 and 2 were applied to the design of the 18-cell reactor stack, which was successfully fabricated and passed all checkout tests. This 7 kW unit designated Buildup No. 3, is displayed in Figure 1. Operational testing of this unit is planned under NASA Contract NAS 9-15831. Under this Orbital Energy Storage Contract, Buildup No. 3 will be operated as a primary fuel cell for approximately 2000 hours, followed by integration and operation with an electrolysis unit as a breadboard demonstration of the regenerative energy storage system.

The progress made during this and previous program phases produced sufficient information for GE/DECP to confidently propose an SPE Fuel Cell Development Program for a second-generation Space Shuttle power plant. Among the significant features projected for this 14 kW fuel cell power plant are:

- Dry weight including accessories - 135 lbs.
- Average HHV efficiency - 52%.
- Operation on propulsion-grade reactants.
- Estimated minimum useful life - 10,000 hrs.
- Estimated production costs - $170K (1979 dollars).

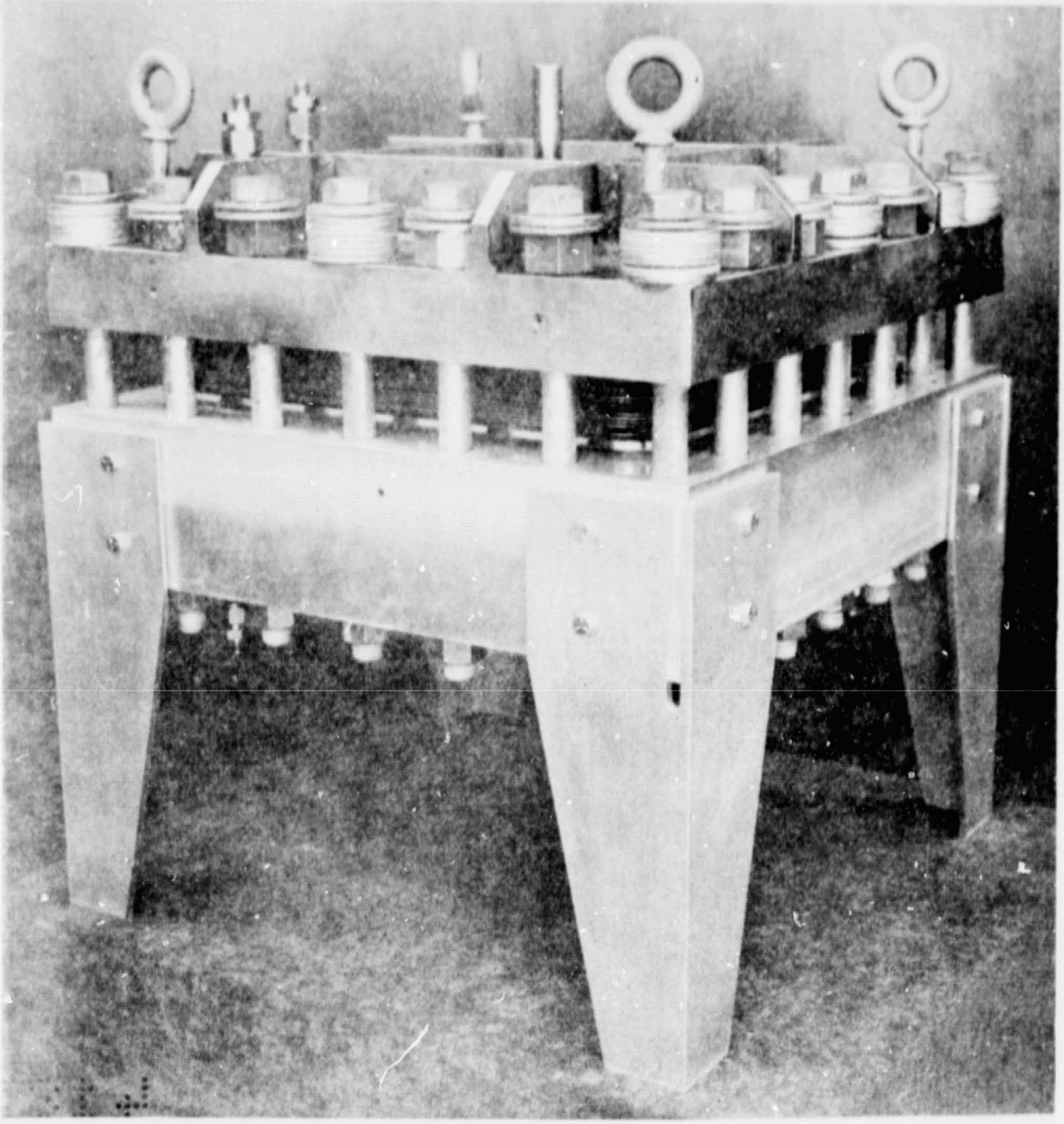

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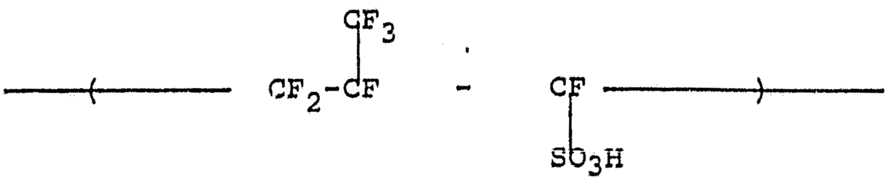
Figure 1. 7 kW Reactor Stack (Build Up No. 3)

2.0 TECHNICAL BACKGROUND

2.1 General Background

The solid polymer electrolyte fuel cell technology was first developed into a viable product in 1960. Over the past 20 years, improvements in both the solid polymer electrolyte and electrode technologies resulted in an increase in the field of applications to include electrolysis systems, oxygen concentrators and regenerative fuel cells. All four electrochemical devices utilize the same basic solid polymer electrolyte and electrode components. Thus, the experience gained from one application can be used in the further improvement of the other devices.

The heart of these devices is the solid polymer electrolyte, which is a plastic film approximately 5 to 10 mils thick, fabricated from ion exchange material. The material currently used as the solid polymer electrolyte has a chemical structure as follows:



This material, called Nafion*, is essentially a sulfonated analog of Teflon*, with physical properties very similar to those of Teflon.

The use of the solid polymer electrolyte as the sole electrolyte in an electrochemical system offers the following advantages:

Minimum weight.

Immobile and invariant during life.

Minimum volume.

Ease of handling during assembly.

Capability of handling high pressure differentials across the membrane.

No tendency to react with CO_2 to form carbonates.

* ® Registered trademarks of E. I. duPont Company.

2.1.1 Solid Polymer Electrolyte Technology

The Nafion solid polymer electrolyte described above is a product of duPont and has been utilized extensively by GE/DECP in electrochemical applications since 1968. This membrane is extremely stable both physically and chemically, while exhibiting excellent physical and electrochemical properties. The specification of these properties is given below:

Property	Value
Tensile Strength	$>$ 2500 psi ($>$17.235 kN/m^2)
Elongation	$>$ 120%
Burst Strength, Unsupported	$>$100 psig ($>$689 kN/m^2 gauge)
Water Content	25-40 Weight %
Resistivity	$>$ 15 ohm-cm
Life in Electrochemical System (hours)	$>$ 57,000 hours demonstrated to date in fuel cells.
Thermal Stability	$>$ 300°F ($>$149°C)

The Nafion solid polymer electrolyte is the latest in a series of GE/DECP membrane systems that included phenol-formaldehyde sulfonic, polystyrene sulfonic, and trifluorostyrene sulfonic acids, and is the only membrane that offered the excellent combination of physical and chemical stability required in the electrochemical environments.

The first Nafion solid polymer electrolytes did tend to degrade slowly in an electrochemical environment as evidenced by a slow generation of HF and CO_2 from the operating device. However, this problem has been rigorously researched by both duPont and GE/DECP and has culminated in a stack of 0.38 ft^2 (354 cm^2) cells that has been operating for over 57,000 hours, with a projected life of over 100,000 hours.

2.1.2 Electrode Technology

The GE/DECP electrode structures are thin catalyst layers pressed onto the solid polymer electrolyte surface. The catalyst/

solid polymer electrolyte electrode also contains a thin (3-4 mil) (.0762-.1016 mm) current collector screen. In order to prevent water masking of the fuel cell oxygen electrode where product water is formed, a wetproofing film is placed on top of the catalyst/current collector. The performance of these electrode structures has been invariant for over 57,000 hours with performance decay of $<1\ \mu$volt per cell hour.

2.2 Major Fuel Cell Programs

The Gemini Spacecraft Program marked the first operational use of a solid polymer electrolyte fuel cell unit. The General Electric GE/SPE fuel cells used during the program successfully completed all seven spacecraft missions, accumulating a total of 850 hours (5000 stack-hours) of flight operation with an excellent record of performance and reliability. The spacecraft system included two 1-kW modules, each containing three 32-cell stacks.

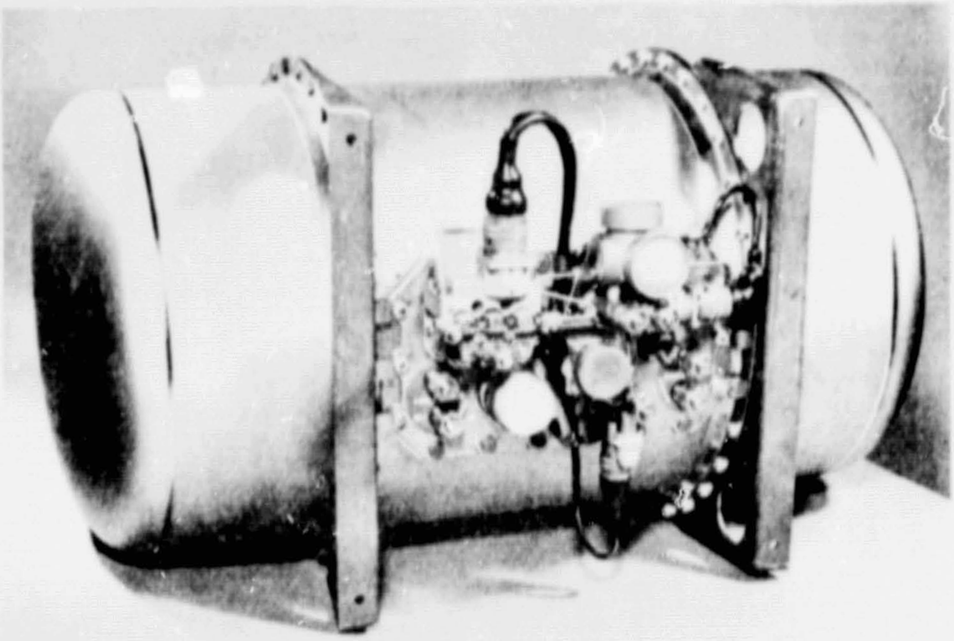
A total of 250 stacks of the production configuration were built during the Gemini Program. Most of these were used for reliability, endurance, and over-stress testing, accumulating more than 80,000 stack-hours of operating experience in addition to that accumulated during flight operation.

Subsequent to the Gemini Program, a second-generation model of this fuel cell design successfully operated in orbit continuously for over 40 days (planned mission of 30 days) on Biosatellite Spacecraft 501. The unit stopped functioning only after the reactants had been depleted. An additional application, the so-called "back-to-back" cell design concept in which cathodes of adjacent cells faced each other, was initially developed for Air Force satellites. Development was continued under NASA's sponsorship.

During the NASA Space Shuttle Technology Development Program, General Electric fabricated and evaluated flightweight fuel cell hardware. Noteworthy is the fact that a 3-cell assembly completed over 6500 hours of life testing, a 38-cell stack operated for 5000 hours, and a 32-cell stack with ancillary components in a prototype flight configuration achieved 2000 hours of operation. The technology developed during the Space Shuttle Development Program was then repackaged as a 3 kW fuel cell for the Navy's High Altitude Super-Pressurized Powered Aerostat (HASPA).

Subsequently, under sponsorship of NASA's Lewis Research Center, initial development of a new solid polymer electrolyte concept was started. The major feature of this concept was the removal of product water via a dynamic recycling oxygen system, as opposed to the traditional wick and separator approach used since the Gemini Program. The advantages of this concept are in the areas of weight, cost and efficiency. This NASA/LRC effort led directly into the NASA/JSC Advanced Fuel Cell Technology Program.

Figures 2 through 4 display the various products described above. Figure 5 is a graphical presentation of the past 18 years of progress in development of GE's solid polymer electrolyte fuel cell technology.



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One kW Fuel Cell Module for Gemini Spacecraft

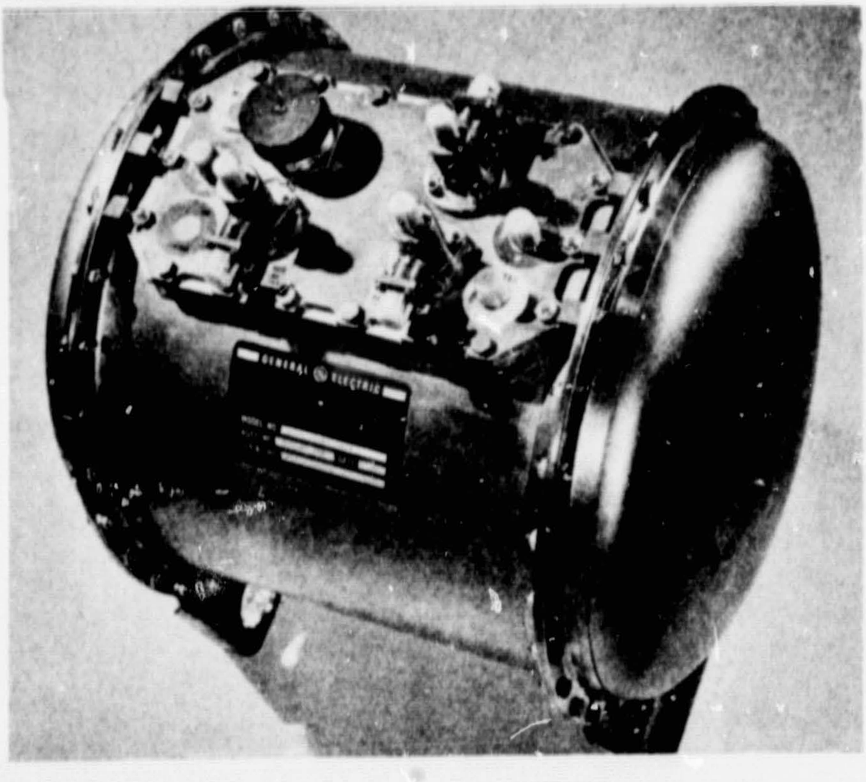

Figure 2. 350-Watt Fuel Cell Module for Biosatellite Spacecraft

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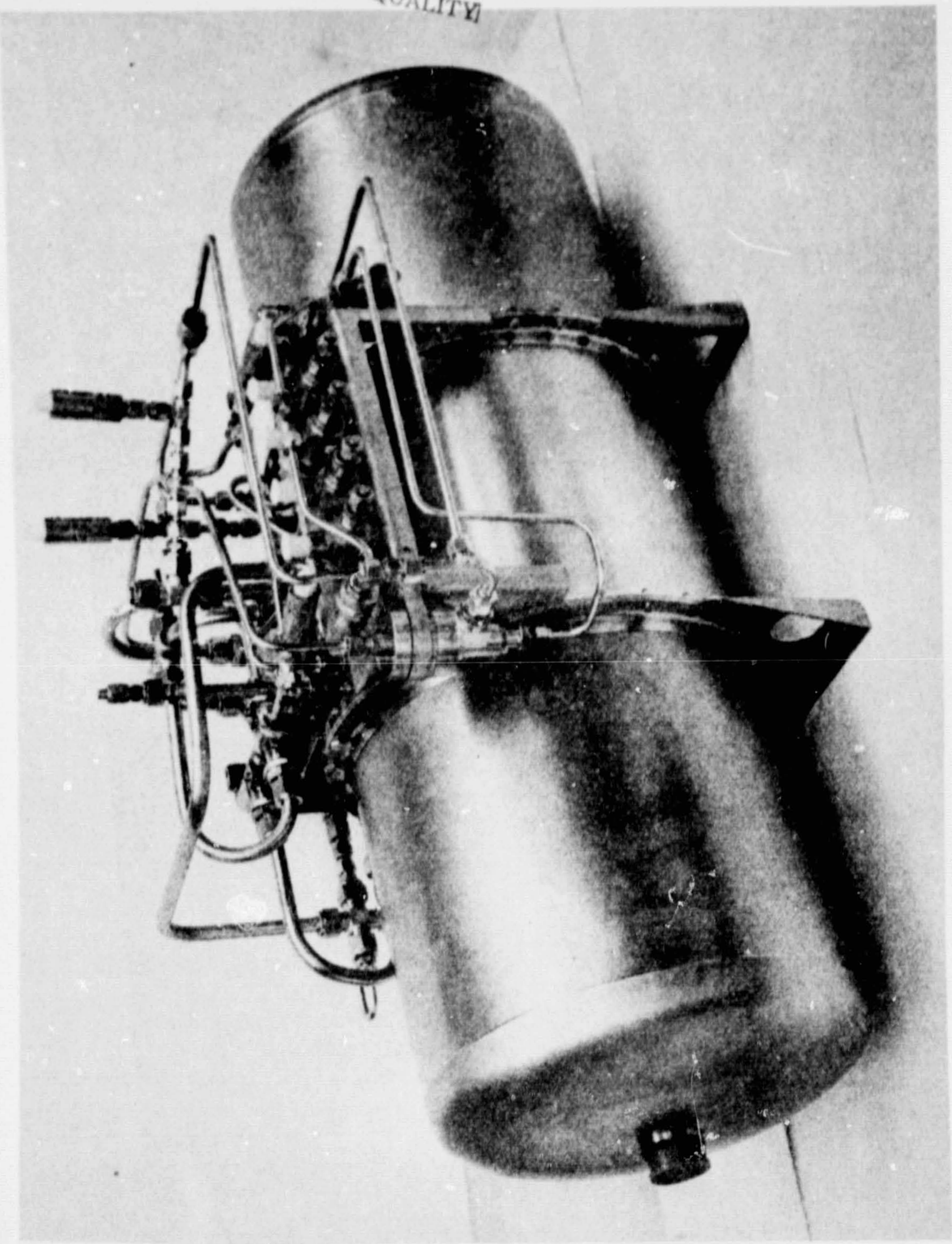
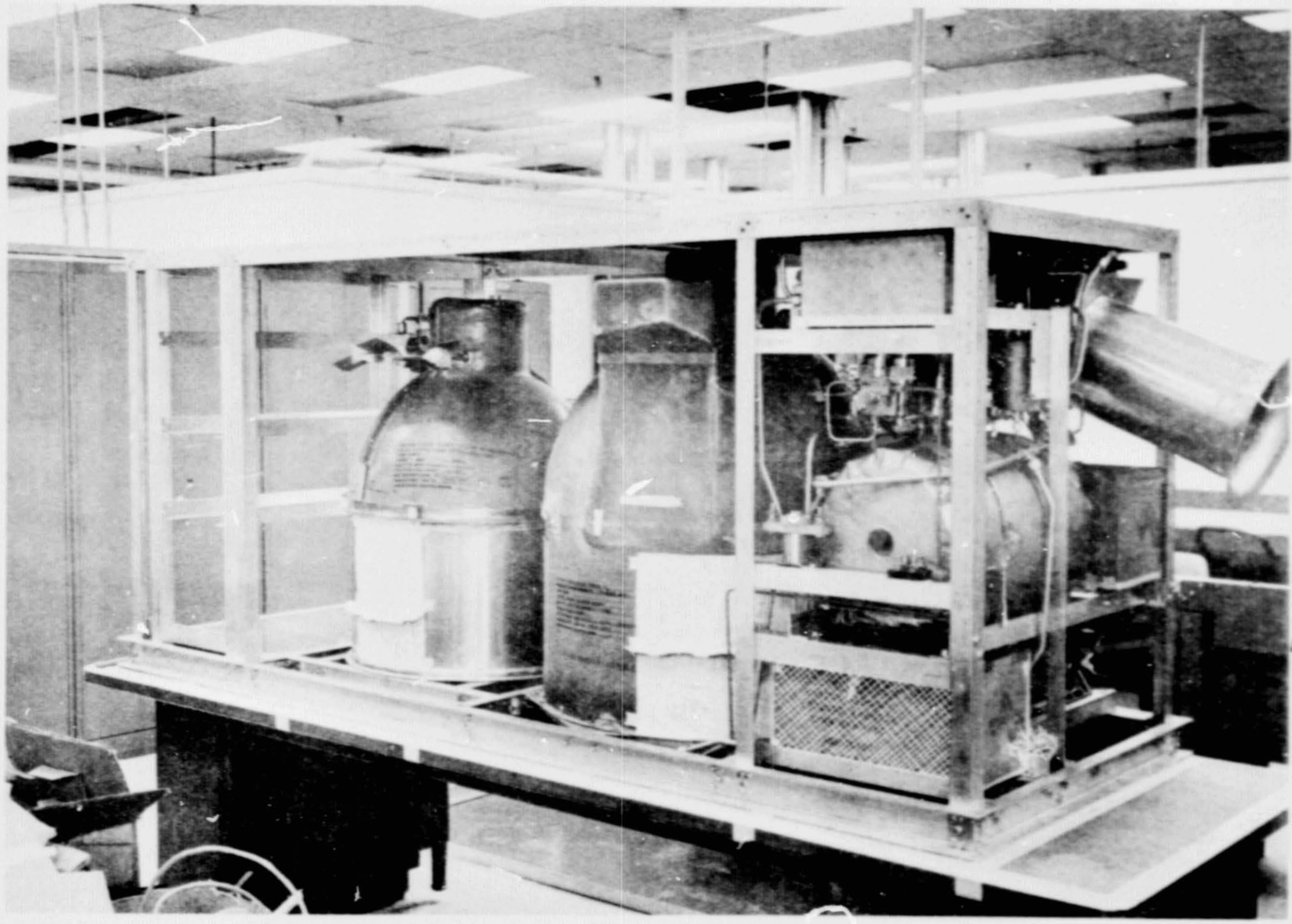


Figure 3. 5 kW Fuel Cell Module with Ancillary Components (NASA/JSC)



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COMPLETE FUEL CELL POWER SYSTEM, INCLUDING CRYOGENIC TANKS, IN THE PROCESS OF ASSEMBLY FOR U.S. NAVY BALLOON PROGRAM

The Fuel Cell Performance Remains at Specification Levels Following 1000 Hours Operation and 2 Years

Figure 4

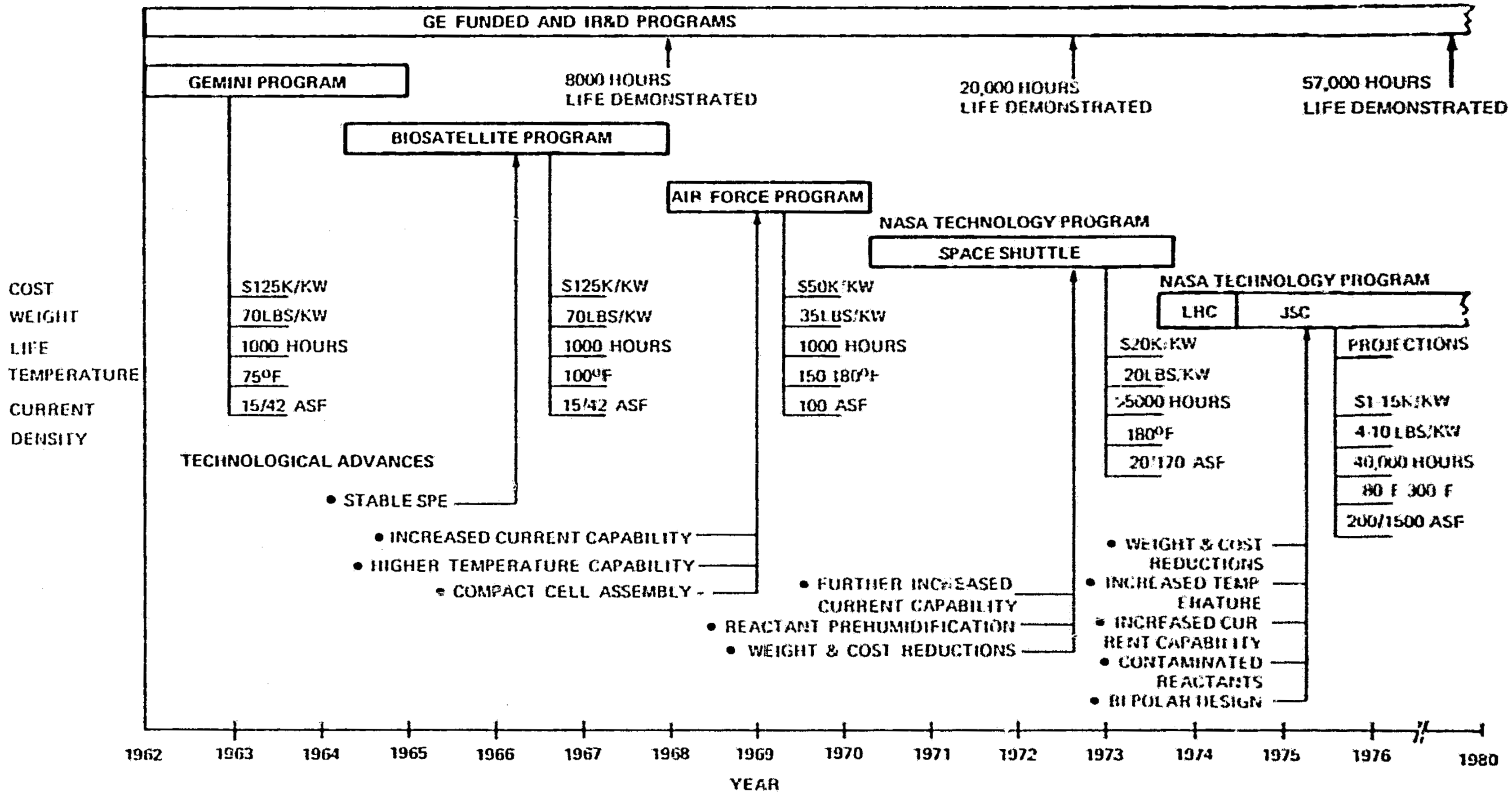

Figure 5. Eighteen Years of Solid Polymer Electrolyte Fuel Cell Technology Development

3.0 TECHNOLOGY ACTIVITIES

The major efforts of the Phase V Program were directed in the following technological areas:

- Task 1.0: Continued Evaluation of Laboratory-Size (3" x 3") Cells
- Task 2.0: Single-Cell Evaluation (Full-Scale Hardware)
- Task 3.0: Small Stack Evaluation (4 Full-Scale Cells)
- Task 4.0: Reactor Stack Evaluation (18 Full-Scale Cells)

Figure 6 shows the overall Phase V Schedule of Efforts.

3.1 Task 1.0 - Continued Testing of Laboratory-Size (3"x 3") and Bench-Scale (.7 ft^2) Cells and Hardware

During both Phase III and Phase IV of this program, a series of endurance and performance tests were begun on laboratory-size cells, the primary purpose of which was to confirm the life and performance characteristics of the SPE fuel cell at temperatures, pressures, and current densitites above those previously demonstrated. These tests were continued in Phase V under Task 1.0. This task was supplemented by efforts under the GE/DECP IR&D Program.

3.1.1 Endurance Evaluation (3" x 3" Hardware)

In order to characterize the performance of any given cell and thus accomplish the goals of this evaluation testing, a baseline configuration was established during Phase III utilizing the state of the art as of 1977. Table I contains a summary of the characteristics of the 1977 baseline cell configuration. Figures 7 and 8 contain performance data as demonstrated during testing under this task during Phase III.

By the end of Phase III, the results of this testing and other developmental efforts led to a reassessment of the configuration being analyzed. It was determined that future performance and endurance analyses under Phase IV would be conducted on cells containing the then recently developed conductive wetproofing configuration. The factors pointing

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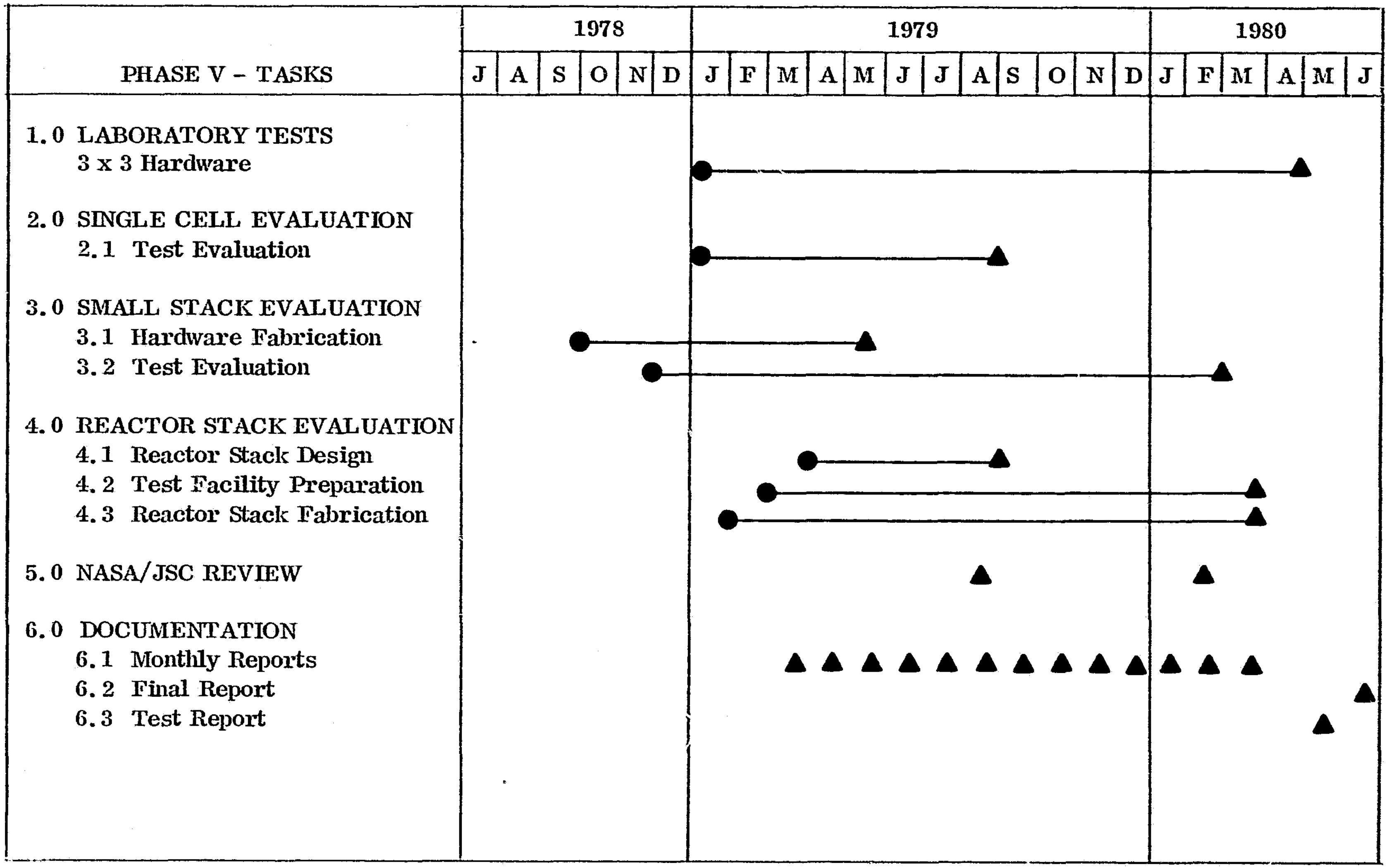
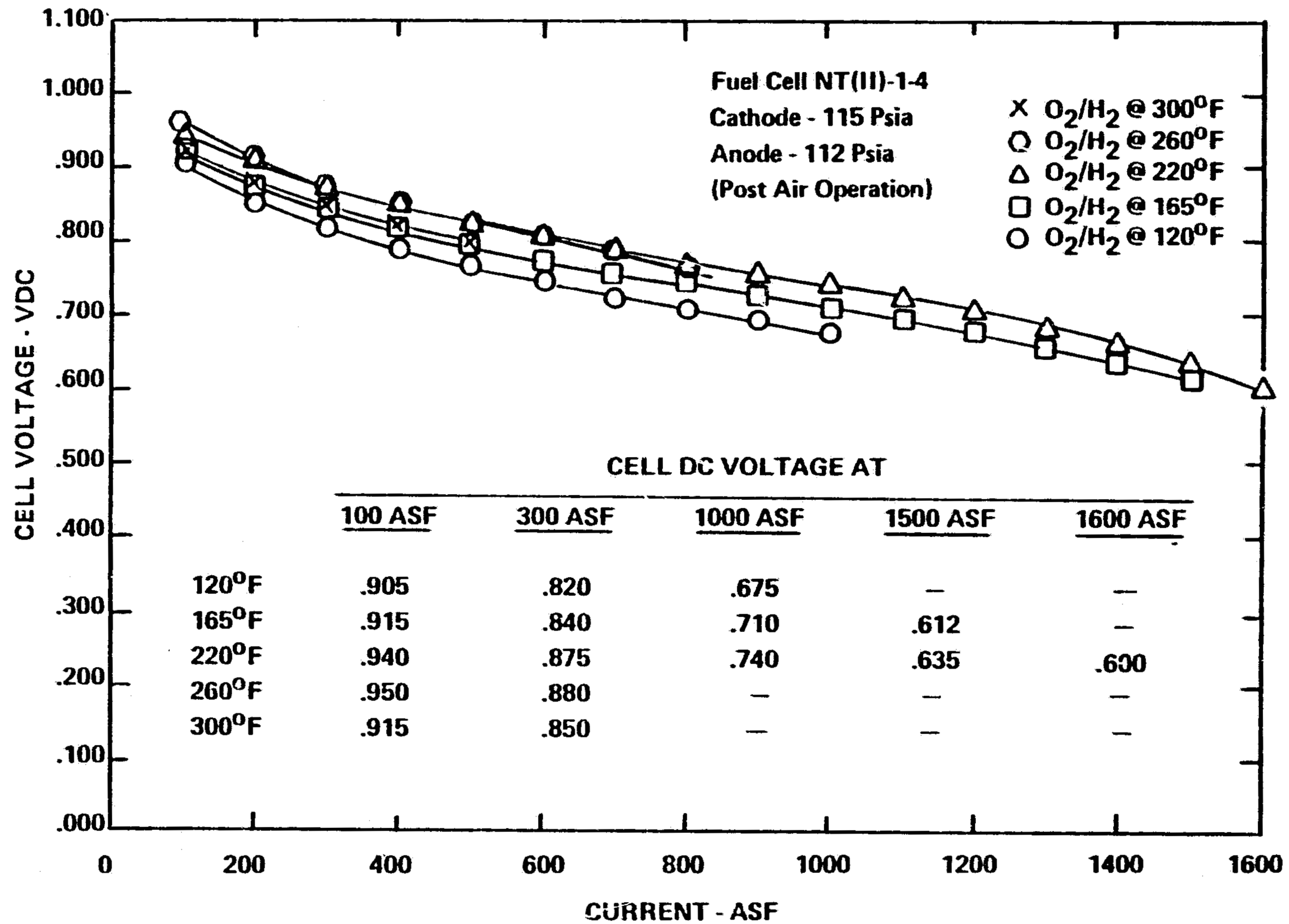


Figure 6

TABLE I

A SUMMARY OF THE 1977 BASELINE CELL CONFIGURATION IS AS FOLLOWS:

- SOLID POLYMER ELECTROLYTE
  - DU PONT'S NAFION
  - 5 MILS THICK
  - 35-40% H_2O
  - 1200 EQUIVALENT WEIGHT
  - PLATINIZED
- ANODE
  - FC-5 CATALYST
  - 15% T-42 (TEFLON)
  - GOLD SCREEN (DISTRIBUTION) ASSEMBLY
- CATHODE
  - PLATINUM CATALYST
  - 12.5% T-30 100% PT (TEFLON)
  - 1/4 INCH STAND PIPE
  - 3 MIL GOLD SCREEN
  - CHEMPLAST WETPROOFING (POROUS TEFLON)
- CURRENT COLLECTION
  - BIPOLAR
  - OPEN CATHODE GAP



	100 ASF	300 ASF	1000 ASF	1500 ASF	1600 ASF
120°F	.905	.820	.675	—	—
165°F	.915	.840	.710	.612	—
220°F	.940	.875	.740	.635	.600
260°F	.950	.880	—	—	—
300°F	.915	.850	—	—	—

Figure 7. O_2/H_2 – High Current Density Performance

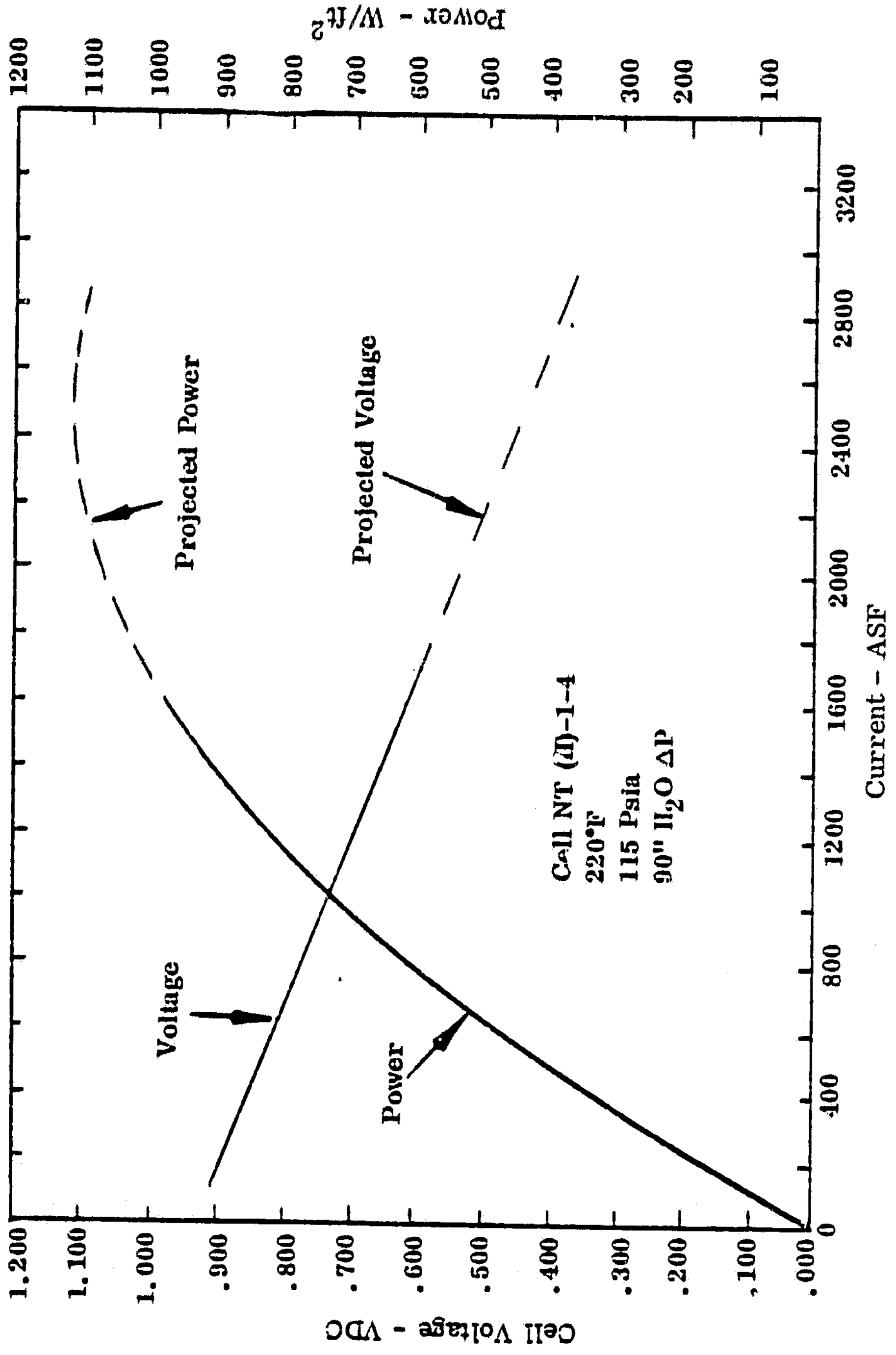


Figure 8. O_2/H_2 - Power vs. Voltage

toward this approach included:

- A cell incorporating this system had demonstrated over 2000 hours of completely stable performance on scaled-up unit NT-03, dispelling the concern that the conductive wetproofing graphite structure might oxidize at operating voltages.

- A conductive wetproofing was desirable for scaled-up hardware to minimize IR losses.

- The conductive wetproofing configuration provided full support to the electrolyte polymer on both sides, and thus facility failures of the type involving oxygen loss would not damage the cells.

- Extrapolated performance from Cell NT-03 and from the 10-mil-thick cells in the IR&D Program with conductive wetproofing demonstrated an equivalent performance between the non-air activated baselines and the non-air activated conductive wetproofing configuration.

- Because the conductive wetproofing configuration eliminated the cathode current collection screen and its 2-3 mil penetration into the polymer, greater structural strength of the polymer resulted by increasing the minimum cross section from approximately 2 mils to 4 mils.

For the above reasons, it was decided to accelerate the conductive wetproofing effort as it continued into Phase IV, and to use cells so configured in the testing under Task 1.0. Figure 9 compares the configuration of the 1977 baseline 3" x 3" cell and hardware to the configuration of the 3" x 3" cell with conductive wetproofing, both as initially developed and as the configuration existed at the end of Phase IV. The initial and final Phase IV conductive wetproofing configurations are pictorially represented in Figures 10 and 11, respectively.

The introduction of the conductive wetproofing configuration into the 3" x 3" endurance test program eliminated the problem of reversed pressure failures resulting from any one of several facility-type malfunctions. However, the endurance testing of the conductive wetproofing cells did exhibit several modes of performance loss and failure not observed in the

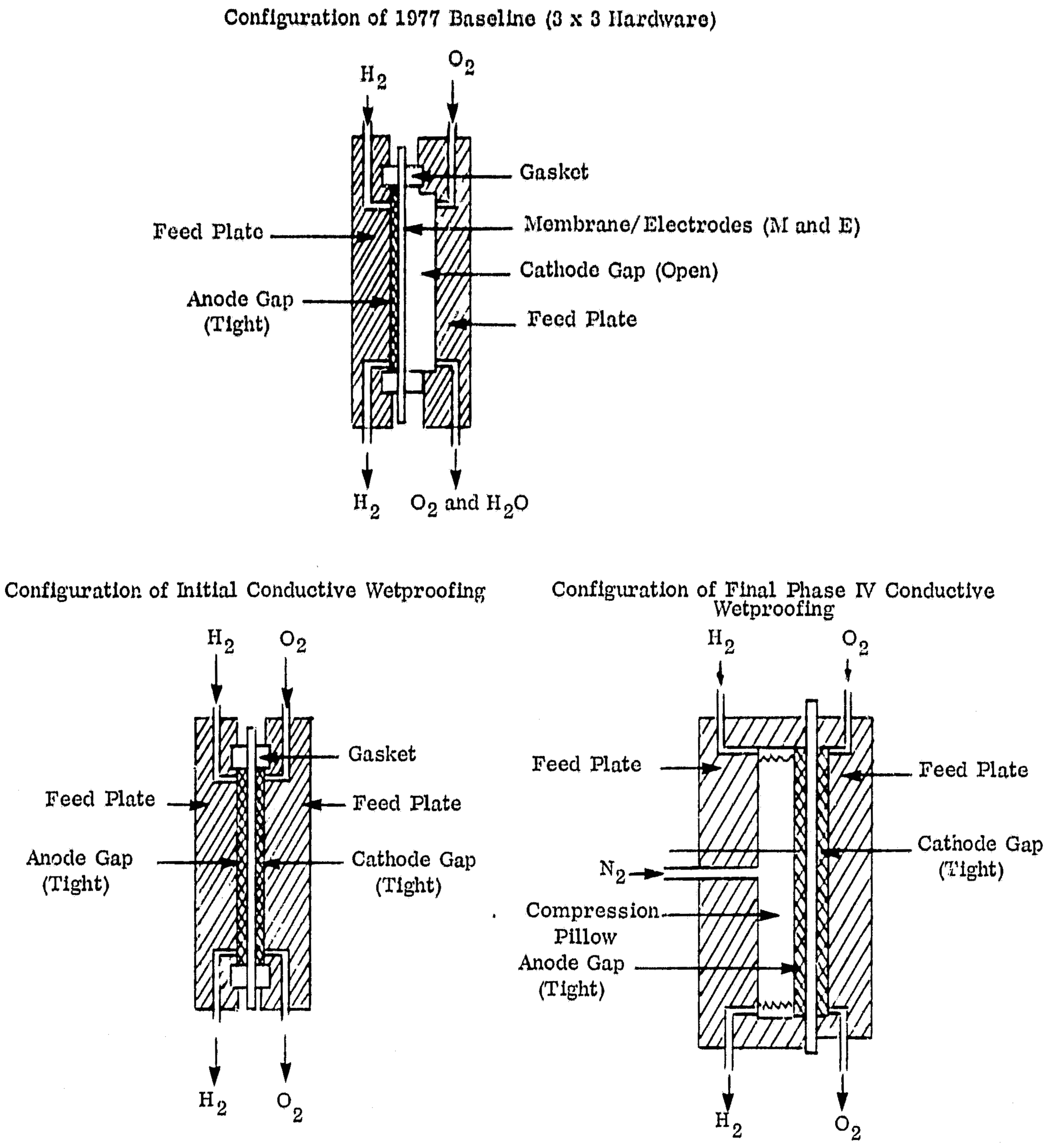


Figure 9. Comparison of Configurations: Baseline vs. Initial Types

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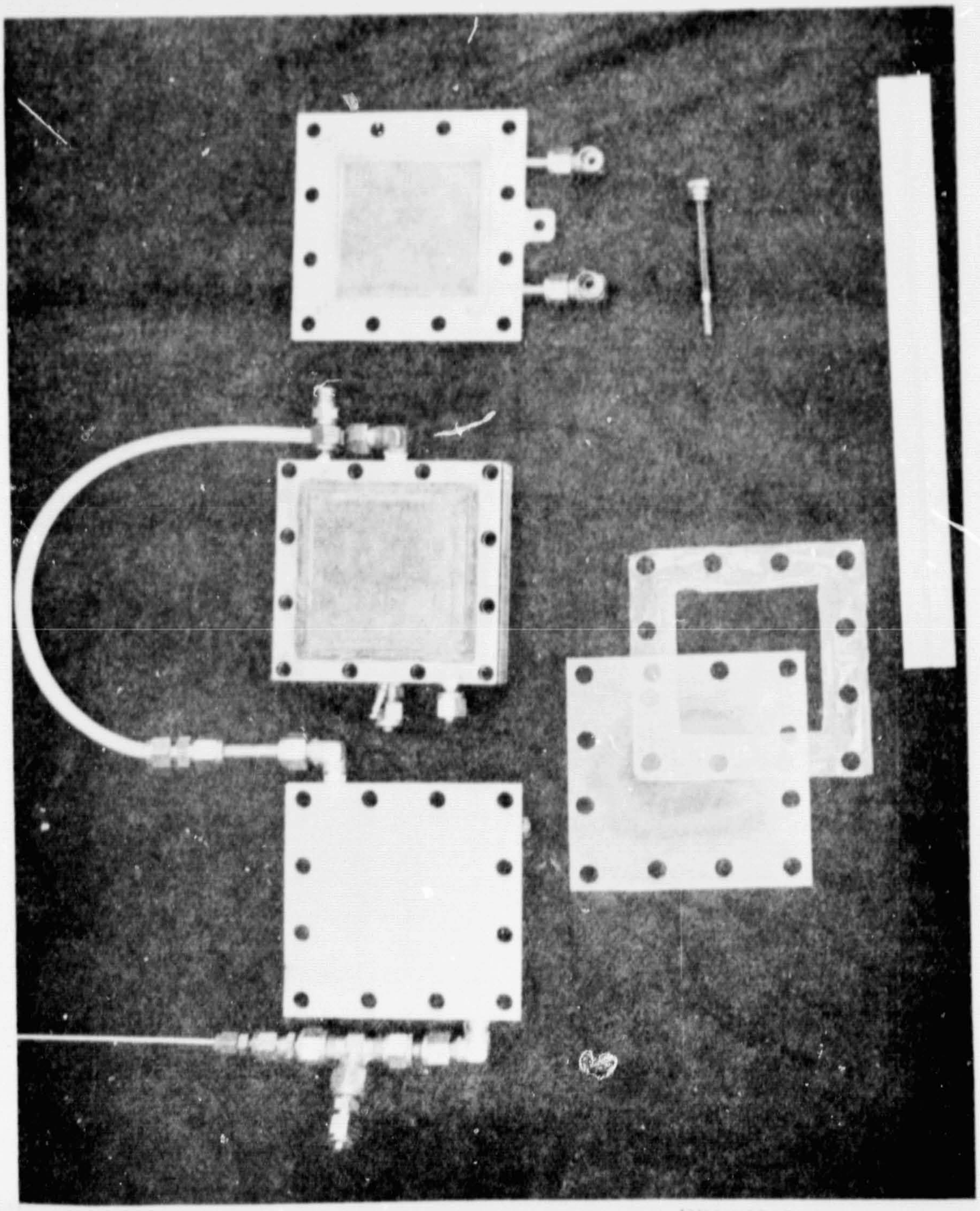

Figure 10. Initial Conductive Wetproofing Configuration

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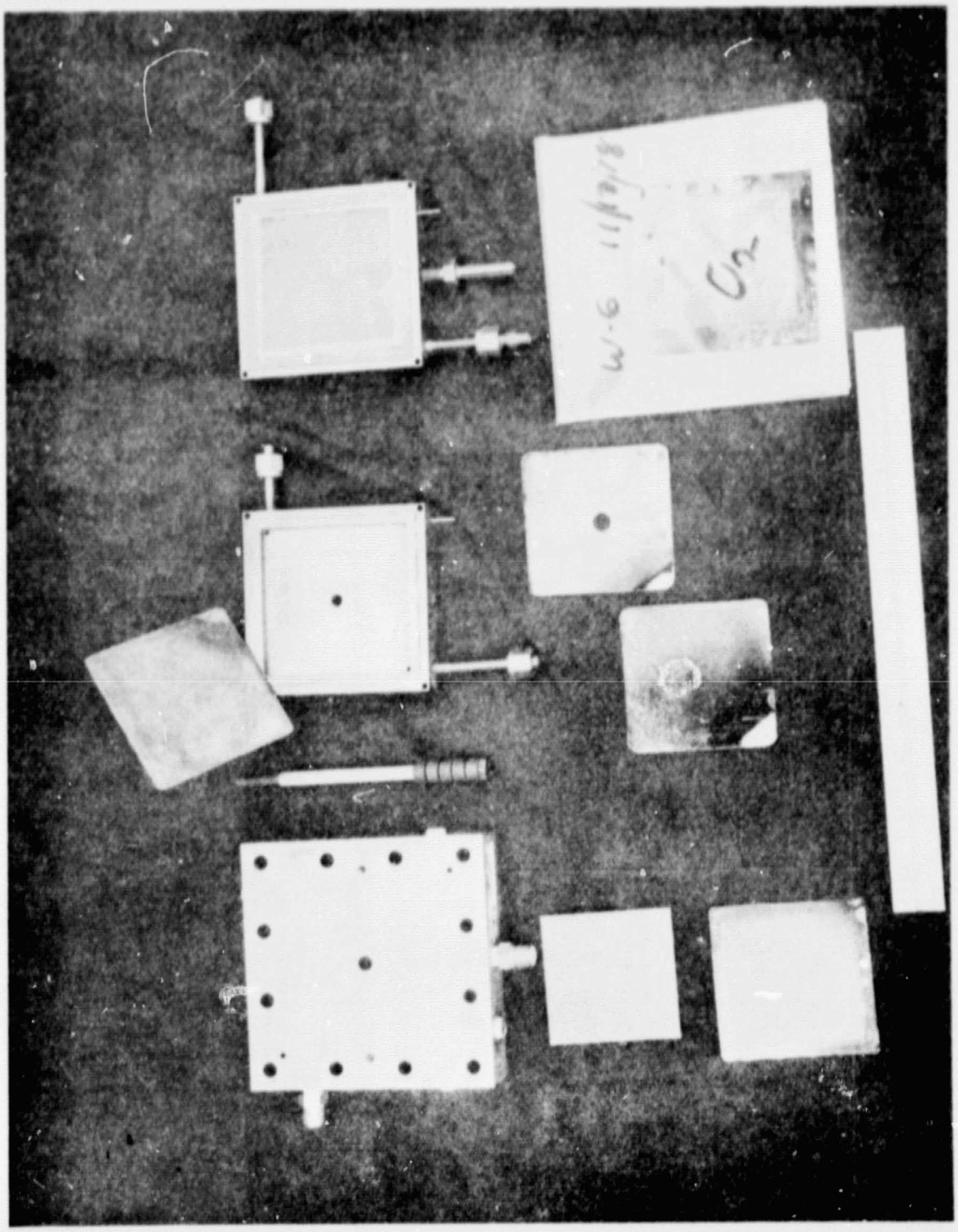

Figure 11. Final Phase IV Conductive Wetproofing Configuration

non-conductive wetproofing configuration. The timing of these events was fortunate, however, in that it was possible to apply corrective actions to the design of the 1.1 ft^2 cell. The major deficiencies identified and corrective actions taken were as follows:

- The solid polymer electrolyte tended to creep with time through the anode expanded-metal flow field screen, eventually resulting in cuts in the membrane. The high compression pressure needed to obtain a perimeter seal and the low cell resistance accelerated this creep process. Corrective actions included incorporation of an independent seal and active area compression configuration, and the introduction of an anode support plate of wetproofed graphite (ST-4).

- Product water flooding of the cell resulted in lower performance. In the previous non-conductive wetproofing configurations, water had been removed by wicks or by gravity. Corrective action included increasing through-cell flow rates of oxygen reactant and redesign of the flow fields.

The culmination of this task under Phase IV was the test of Cell NT(IV)1.1-13, which successfully ran for 3,926 hours at the operational conditions planned for the 1.1 ft^2 cells. The cell developed a cross-electrolyte leak at this point in the test and was shut down for a teardown analysis conducted at the start of Phase V. The analysis revealed that the cross-electrolyte leakage was due to a pinhole in the central area of the membrane (i.e., not near any reactant porting.)

Removal of the catalyst electrodes revealed:

- Membrane flow around the anode 5/0 Zr support screen.

- General evidence of central area (not ports) degradation of the membrane.

The postulated cause of failure was the combined effect of partially degraded membrane and membrane flow around the 5/0 screen support. The membrane flow condition was subsequently mitigated by the use of a porous graphite flow field support, later incorporated into the 1.1 ft^2 design. The presence of

general degradation raised some concern, in that this condition had previously been observed only at reactant inlets where subsaturated reactants were utilized.

The central area degradation suggested that some heat and mass deviation had occurred in the dual compression hardware. A thermal analysis of the hardware indicated that 5 to 10 times as much waste heat produced was removed from the cathode side as from the anode side. The major reason for this condition arose from the nitrogen gap in the anode pressure pad which was located between the cell and the anode side coolant. The cathode heat removal was in the opposite direction from that desired, and produced a drying gradient within the cell. It was well established from previous studies that the rate of membrane degradation is influenced in a major way by the degree of membrane drying.

The process of cathode heat removal, which causes drying of the membrane was prevented in the scaled-up 1.1 ft^2 design by having a slightly higher thermal impedance from the cell to the cathode side coolant than from the cell to the anode side coolant.

As a result of the adverse thermal gradients identified, a revision of the 3" x 3" test hardware was conducted. The major features of the revision included:

- Nearly equal heat removal from the anode and cathode sides.
- Use of distilled water as a coolant instead of oil, which had been utilized for all previous 3" x 3" tests.
- Use of an anode support sheet of porous ST-4 graphite instead of expanded-metal screens.

The above corrective actions in the laboratory-scale 3" x 3" hardware actually produced a design with a close resemblance to the scaled-up 1.1 ft^2 hardware design.

A 3" x 3" cell designated NT(V)1-1 was cut from a 1.1 ft^2 cell for a performance analysis of a section of that full-scale cell. Activation and operation of Cell NT (V)1-1 revealed a performance level approximately 0.010 volt higher than that of Buildup No. 1 (see Figure 12). Life endurance testing of Cell NT(V)1-1 at 180°F and 115 psia remains in-process as of this

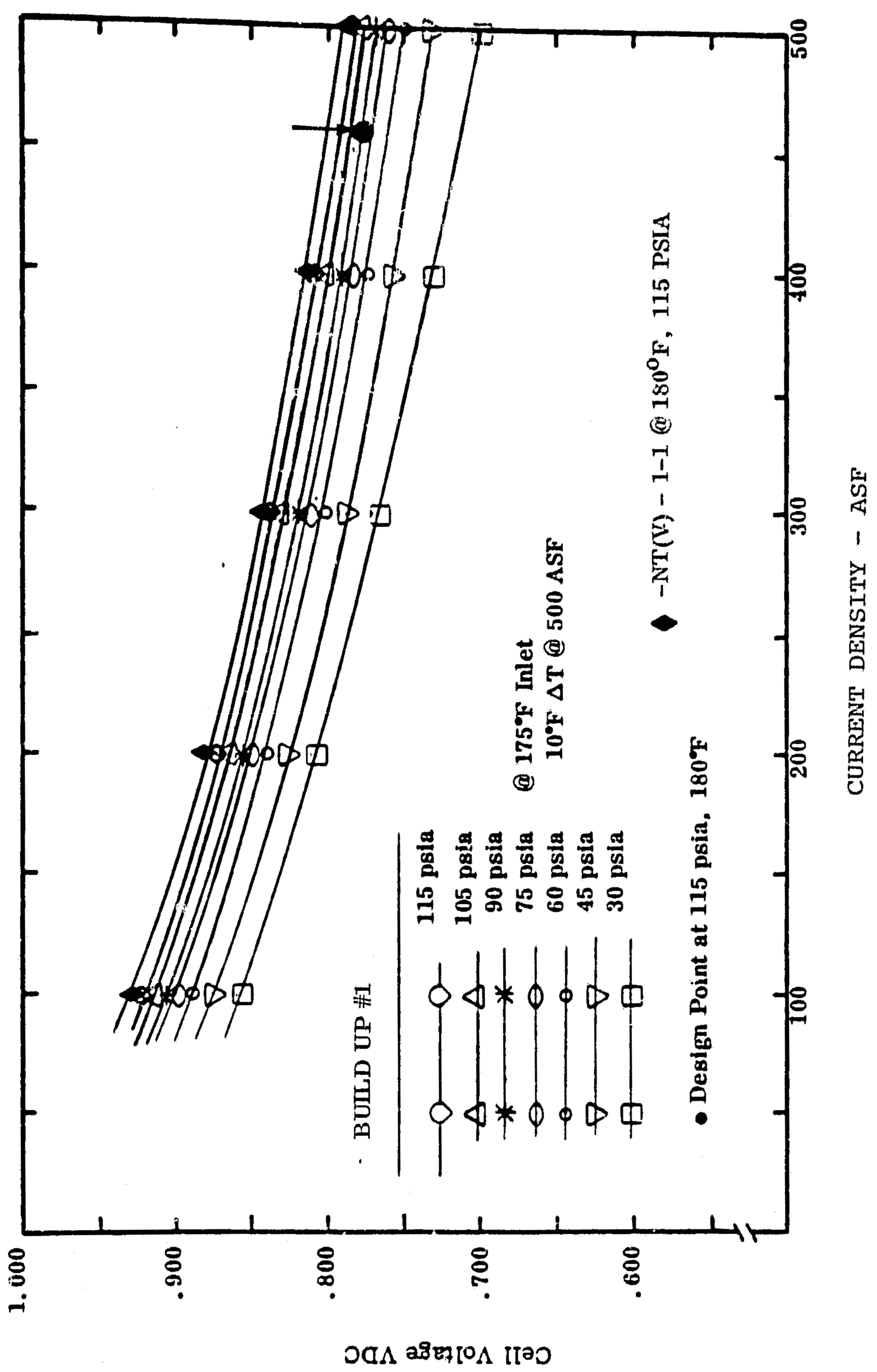

Figure 12. NT(V) - 1-1 vs. Buildup #1 & Design Goal

writing, the cell having accumulated over 4300 hours of virtually invarient performance to date (see Figure 13). Continued endurance testing of this cell is being conducted as part of the GE/IR&D Program.

3.1.2 NT-03 (.7 ft^2 Development Cell) Performance

The purpose of this subtask was to demonstrate that the advances made in 3 x 3 laboratory-sized cells and hardware could be scaled up and applied to larger cells. The size of .7 ft^2 was established early in the program (Phase I) as a likely intermediary between the 3 x 3 cells and full operational size.

NT-03 began load operation on October 4, 1977, during effort under Phase III. This cell incorporated new design features generated as a result of the GE/DECP IR&D effort on conductive wetproofing. These modifications to the earlier NT-02 design included:

- Corrugated titanium coolant system trusses to replace the polypropylene screens.
- Conductive wetproofing to replace the interrupted Teflon wetproofing.
- Frame porting to replace port trusses for improved stack up.
- Reduction in thickness of Nafion electrolyte from 10 mils to 5 mils.

Figure 14 shows a cross-section of this stack.

By the end of Phase III, Cell NT-03 had accumulated 3,388 hours of extremely stable performance at 16 psia and 165°F. Testing of this cell continued into Phase IV, the cell operating for a total of 5,819 hours before a facility power loss resulted in a shutdown and normal oxygen takeover. Figure 15 displays cell NT-03 performance levels during the test. The HF release rate had remained in the 50 - 150 PPB range throughout.

During checkout prior to reactivation, both excessive cross-electrolyte and overboard oxygen leakage were observed. Teardown analysis revealed two factors which were related to the leakage conditions:

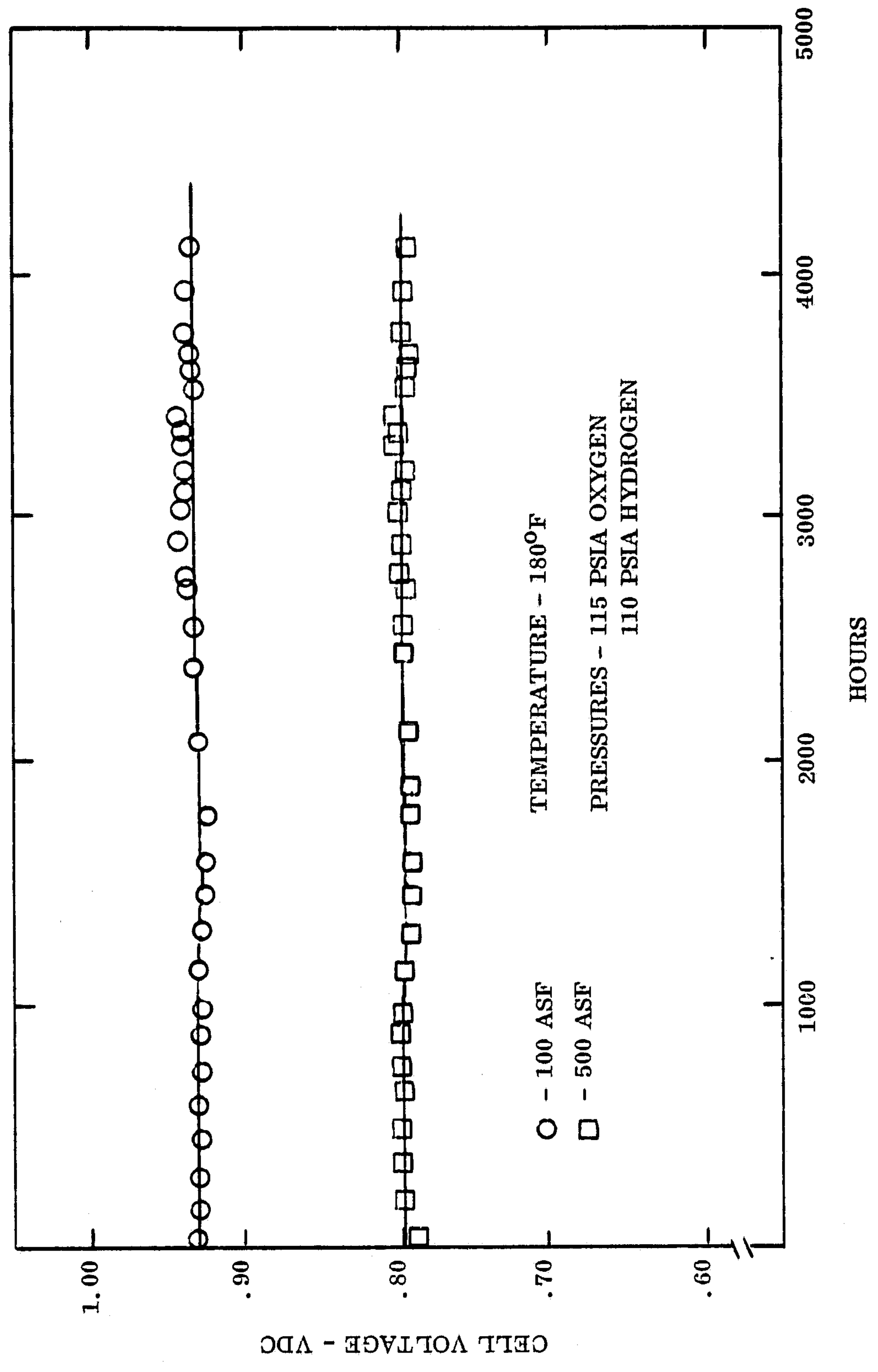

Figure 13. Cell NT(V) - 1-1 Endurance

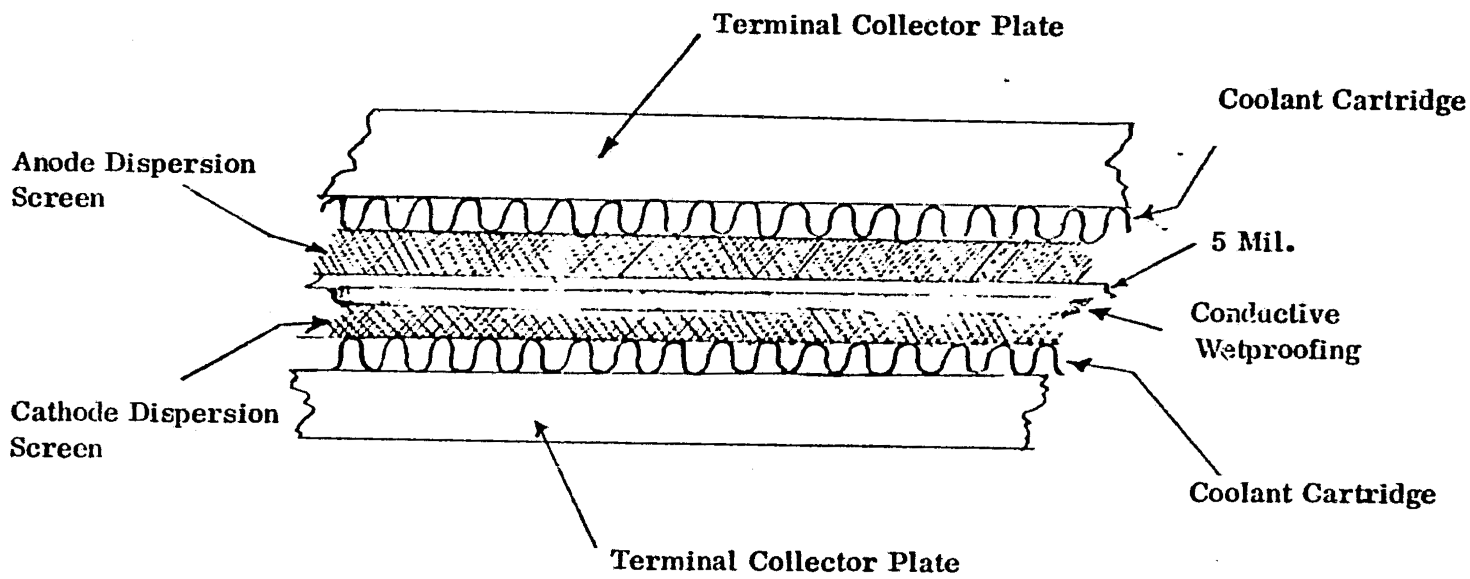

Figure 14. NT-03 Cross Section

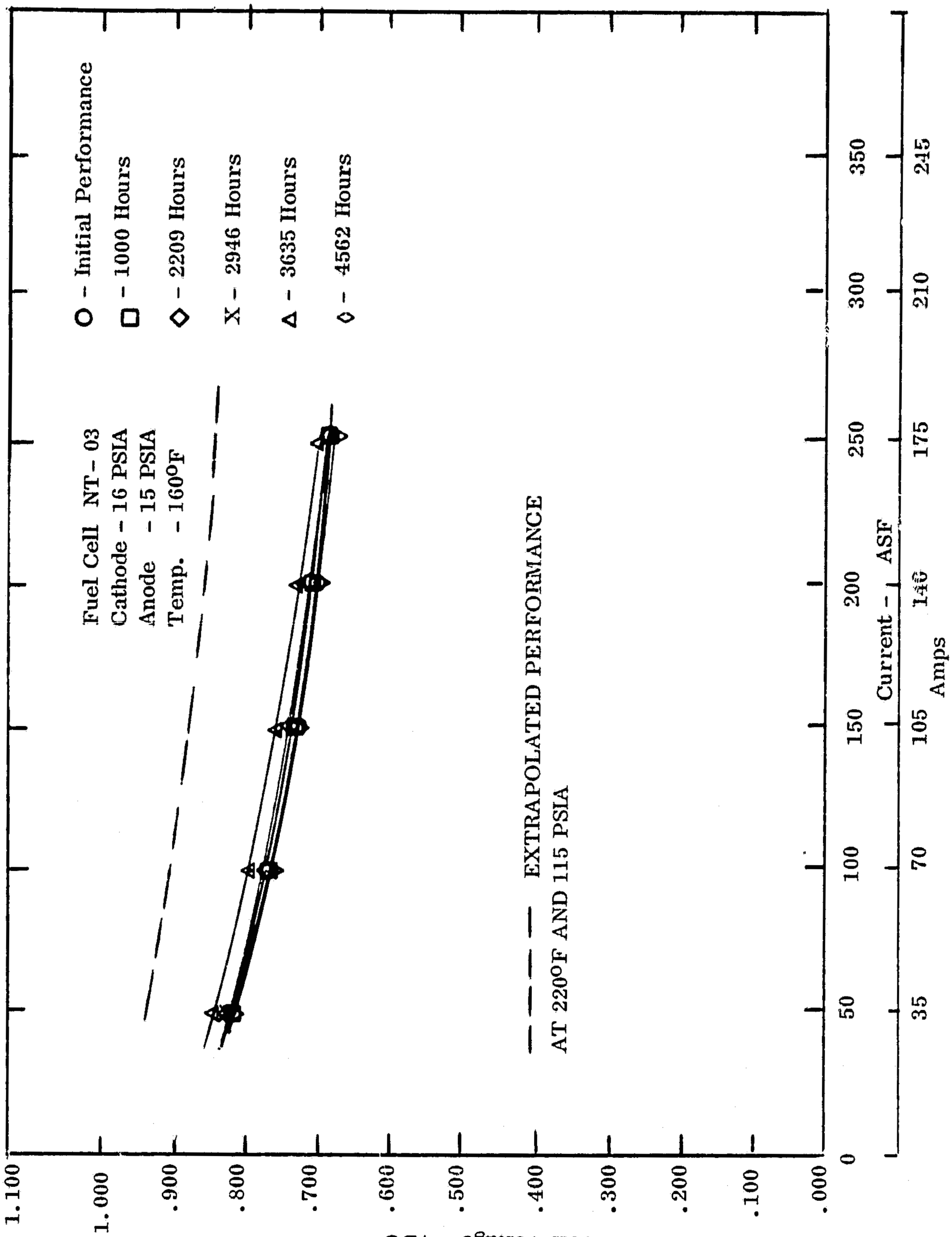

Figure 15 - O_2/H_2 Performance

- The Teflon double-sided adhesive frames had undergone some creep with operational time, and the stack compression load in the perimeter seal area was considerably reduced.

- An original time-zero screen puncture, which had been successfully patched with Teflon and silicone adhesive before initial activation, was found to leak at tear-down. This original screen puncture resulted from misalignment of the oxygen flow distribution screen package.

The overboard leakage was undoubtedly the result of the loss of seal area compression, whereas the cross-electrolyte leakage could have arisen from either of two probable causes:

- With decreased seal area compression, cross-manifold O_2-to-H_2 leakage could have occurred.

- The original puncture could have opened during the flexing of the electrolyte as the automatic oxygen takeover shutdown proceeded.

The electrolyte damage which occurred as a result of the facility power failure was repaired with Teflon and silicone adhesive, and the unit was reassembled with tie rod springs. Following installation of the unit into the test facility, a series of leakage, flow and electrical checkout tests indicated that all was normal.

The unit was activated, and performance appeared normal at room temperature. As the operational temperature of the unit was increased, the normal performance improvement was noted. After approximately nine hours of operation in an unattended mode, a slow performance decrease developed. This decay continued over a two-hour period until a low-voltage shutdown resulted.

An analysis of the NT-03 shutdown was conducted at the beginning of Phase V. A coolant system leakage check showed a substantial leakage from the coolant to the hydrogen chamber. Small cracks were identified as the leakage source in the 3-mil niobium anode flow field.

Samples of the leaking 3-mil niobium hydrogen/coolant separator sheet were subjected to tensile-test evaluation.

Samples of unused 3-mil niobium from the same lot, and from the 3-mil niobium oxygen/coolant separator sheet, were also tensile-tested. The unused material and the oxygen separator material demonstrated approximately the same tensile strength. However, the hydrogen separator sheet demonstrated only 50% of the tensile strength of the oxygen and unused samples. Hydrogen embrittlement was therefore considered a potential failure mode to be addressed in the desired life range over 5000 hours. Previous experience of embossed 3-mil niobium up to the 5000-6000 hour range had been good (i.e., no metal sheet failures identified). The NASA 1.1 ft^2 design incorporated a 5-mil separator for hydrogen and coolant in an effort to mitigate the embrittlement to the extent that design life of >10,000 hours may be achieved.

New niobium separator sheets were fashioned for NT-03 utilizing the thicker 5-mil material. Re-assembly of NT-03 utilizing these new sheets was completed and the unit was re-activated. Life testing was continued at the previous temperature and pressure conditions of 165% and 16 psia. As of this writing, over 11,000 hours have been accumulated on the unit, approximately 5000 hours of which involve the new 5-mil flow field collectors. The endurance testing of NT-03 is continuing under the GE/IR&D Program.

3.2 Task 2.0 - Single-Cell Evaluation

The objectives of the design and development testing of Buildup No. 1 were to incorporate recent laboratory advances into a full-size cell and to duplicate the performance obtained in laboratory-sized cells. B/U No. 1, featuring electrically conductive wetproofing and 5-mil thick Nafion electrolyte, performed slightly better than the performance goal based on laboratory cell tests. Figure 16 displays the goal and the actual performance of B/U No. 1.

The active area of the B/U No. 1 cell design was selected at 1.1 ft^2 by computer optimization which considered the potential near-term space applications. A 14 kW module would require 36 cells of this size, and it is estimated that such a module will have a total weight of approximately 150 pounds (10.7 lb/kW), including the weight of end plates and ancillaries as well as the weight of the coolant.

Buildup No. 1 accumulated over 3200 hours of invariant performance over the current density range between 100 and 500 ASF. The unit ultimately shut down as a result of a failure of a facility-associated oxygen solenoid valve. All testing was performed utilizing commercial-grade reactants.

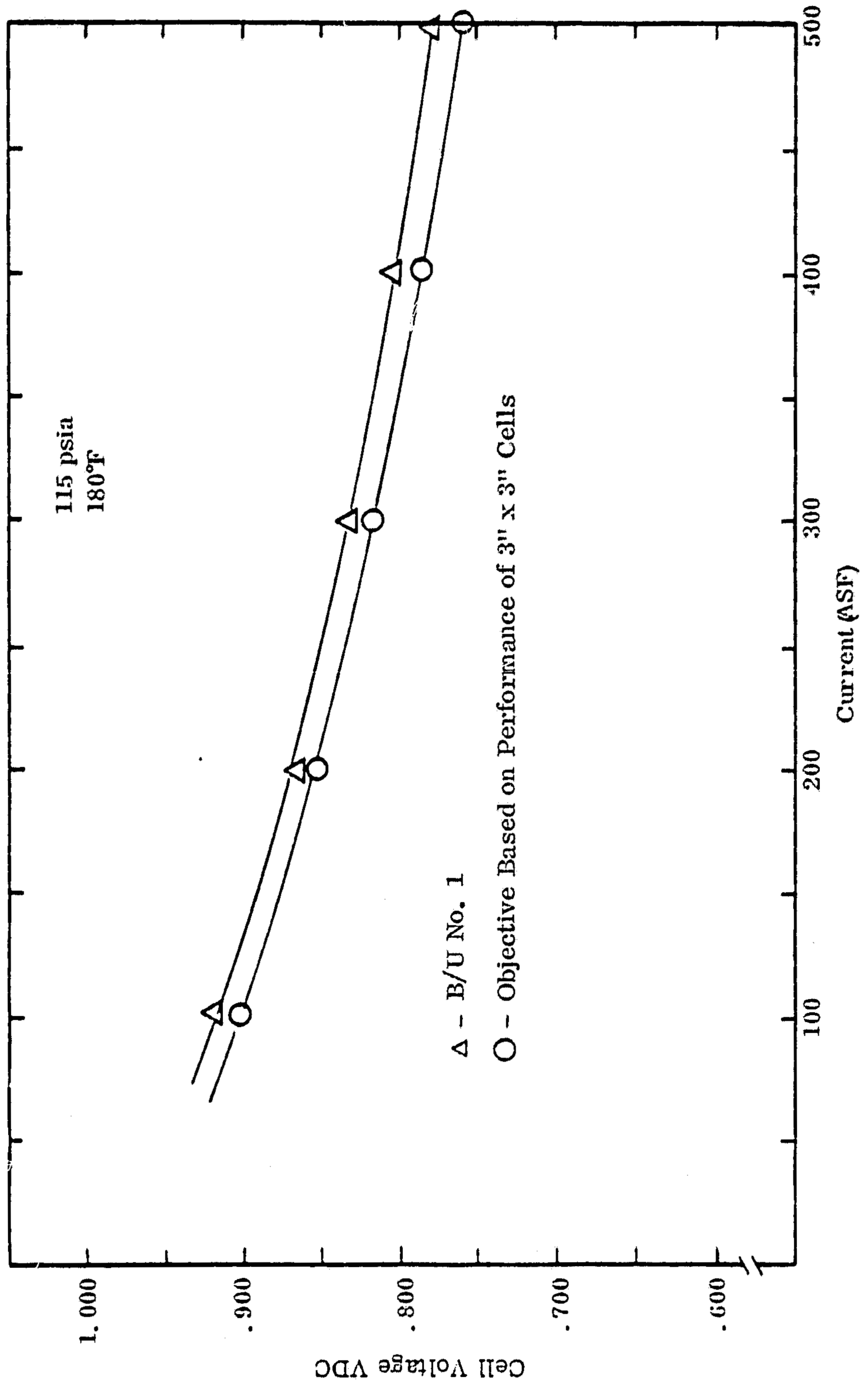

Figure 16. O_2/H_2 Performance Comparison

The following are the highlights of the experience gained on the 1.1 ft^2 cell test in B/U No. 1:

- The performance level of B/U No. 1, having duplicated and slightly exceeded the goal set by lab-size cells, verified the scalability of the solid polymer electrolyte technology.

- The stable performance exhibited by B/U No. 1 for over 3200 hours verified previous evaluations displaying $<1\ \mu$volt decay per cell-hour of operation at high current densities (see Figures 17 and 18).

- The low HF release rate in the B/U No. 1 product water (<50 PPB) is within the same range exhibited by B/U AFC-6, which has a demonstrated life to date in excess of 57,000 hours.

- Through independent bench-testing, the higher-than-desired oxygen ΔP observed in B/U No. 1 was discovered to be located largely within the internal cell manifolds. Repositioning the ports from the corners to the mid-side reduces the ΔP significantly by cutting the max flow path in half, and the max volume flow in each manifold in half. This reconfiguration was introduced into B/U No. 2, and thus it was possible to eliminate the cathode expanded-metal screen on this unit.

- The teardown and destructive analysis performed after over 3400 load hours of operation showed no evidence of any materials degradation, further confirming long-term life capabilities.

3.3 Task 3.0 - Small Stack Evaluation

Buildup No. 2 featured the same basic design as Buildup No. 1, only in a 4-cell configuration. Minor modifications were incorporated into the end plate, the oxygen flow field, and the coolant cartridge frame.

The oxygen flow field and end plate modifications were introduced into Buildup No. 2 to reduce this oxygen flow field pressure drop and to eliminate end plate leakage, respectively. The coolant cartridge frame modifications were made to reduce cost.

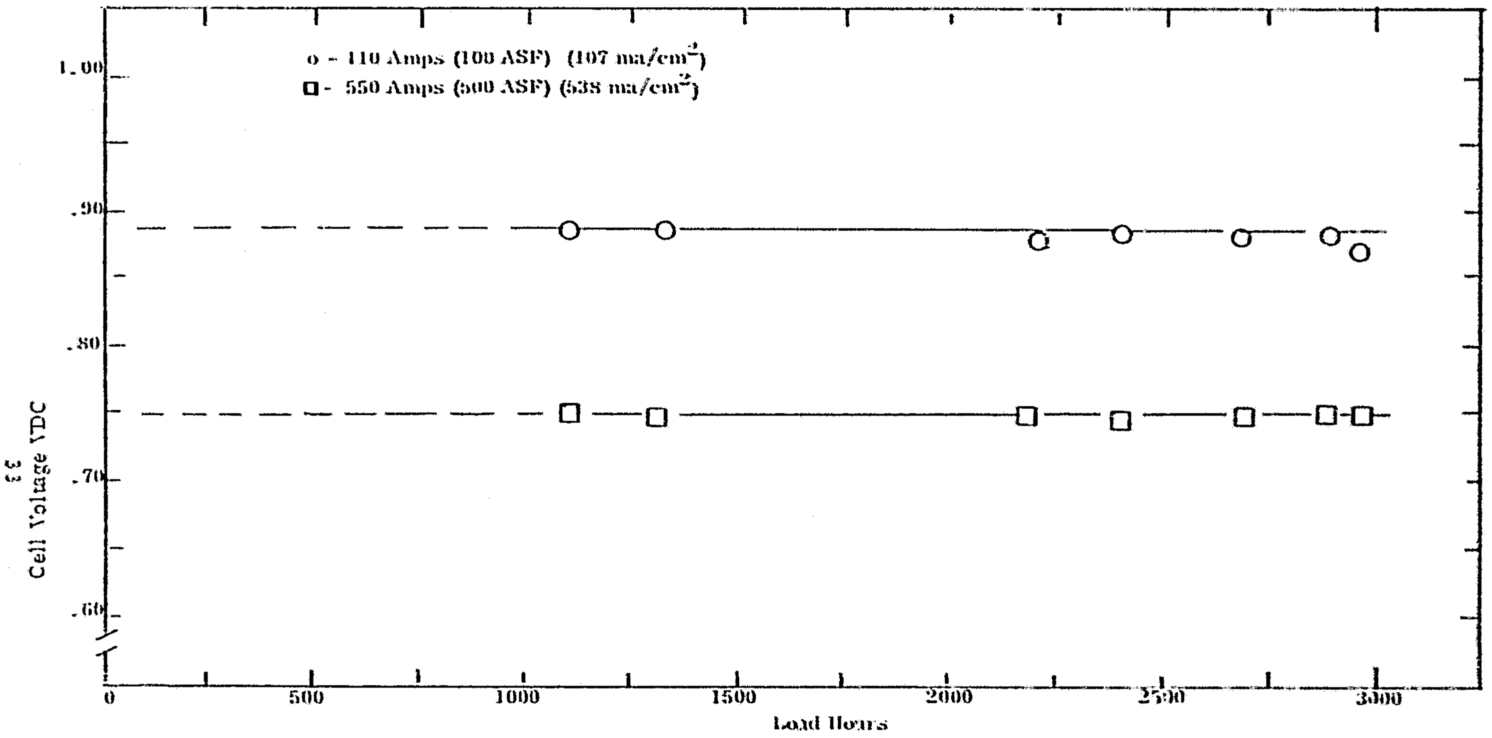

Figure 18. B/U No. 1 Performance Stability at 60 psia Reactant Pressures and 180°F

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Over one thousand hours of test experience were accumulated on Buildup No. 2. The following are the highlights of the small stack evaluation task:

- The double "O"-ring and piston modifications to the pressurization end plate eliminated the leakage problem encountered with the elastomeric-sealed end plate on Buildup No. 1.

- The re-positioning of the oxygen manifold had the effect of approximately halving the oxygen flow field ΔP as compared to that of Buildup No. 1.

- The use of the low-cost single piece coolant cartridge frame with separate coolant manifold ports appeared to provide normal functions without difficulty.

- It was learned that component stack-up tolerances must be maintained without exception in order to assure a leak-tight stack configuration.

3.4 Task 4.0 - Reactor Stack Evaluation

Buildup No. 3 utilized the same basic design as Buildup No. 2 while increasing the number of cells from 4 to 18. In addition, the following modifications were introduced as a result of the short stack evaluation task:

- Closer tolerance on the coolant cartridge frame thickness variations, to improve cell sealing.

- Increased seal area on reactant manifold buttons, to accommodate minor stack-up variations.

- Improved membrane and electrode processing, to assure consistant cell resistance and electrical performance.

In parallel with the Buildup No. 3 design task, a GE/DECP IR&D effort to develop a failure isolation device was in-process. The isolation concept involved installing an "O"-ring check valve in the inlet and outlet cell manifold buttons. In this concept, with the oxygen reactant always at a higher pressure than the hydrogen reactant, any failure resulting from cell leakage would be confined to the failed cell and the hydrogen outlet manifold only. Propagation of mixed and/or hot combustion gases to other cells is thus prevented and damage to other cells avoided. Figure 19 displays the configuration of the hydrogen manifold buttons, while Figure 20 exhibits the same buttons with the O-ring check valves.

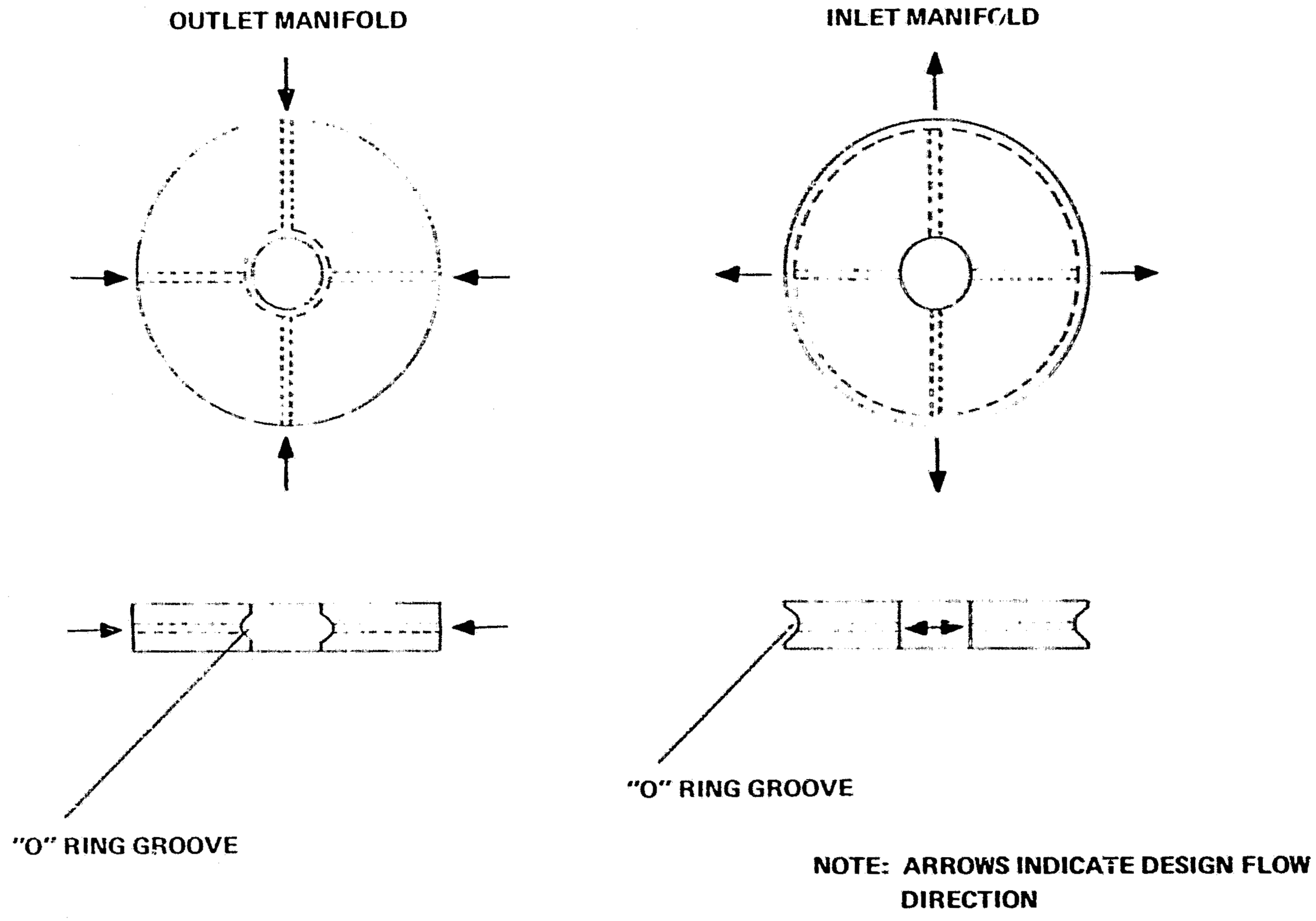

Figure 19. Failure Isolation Manifold Buttons

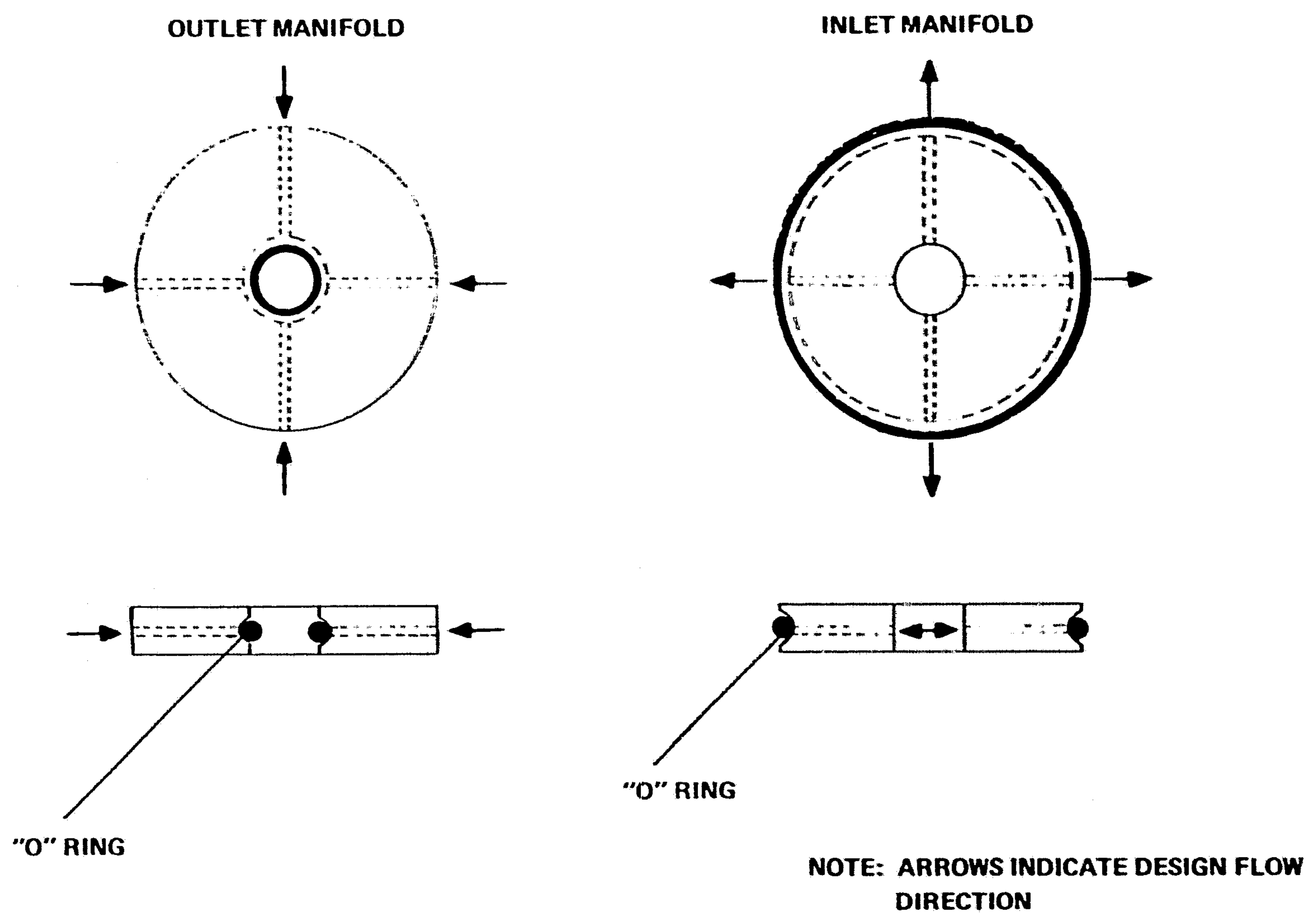

Figure 20. Failure Isolation Manifold Buttons with "O" Rings

The GE/DECP IR&D testing of this concept included flow and simulated failure tests. The results of which verified that propagation of a failure could be prevented by this technique. Thus, it will only be necessary to replace the cell that actually failed in the event of a cross-electrolyte leakage during operation.

The hydrogen manifold buttons in Buildup No. 3 were fashioned with the "O"-ring grooves in place; however, the actual "O"-rings were not installed as variable normal flow direction pressure drops would probably result. With the high-purity fuel cell or propulsion-grade hydrogen fuel, the minor variations in pressure drop would have no consequence. In the testing at GE/DECP, using commercial-grade hydrogen, the uniformity of flow field pressure drop is of more importance in the inert removal process. Additional evaluations of pressure-drop variability must be completed prior to incorporation of the O-rings. The O-ring grooves were added, such that the hardware can be retrofitted to include the O-rings at a later time without replacing on reworking the coolant cartridge assemblies.

Buildup No. 3 was assembled with the aforementioned design modifications into a 7 kW - 18 cell reactor stack. All electrical tests were performed, with satisfactory results. The results of cross-electrolyte and overboard leakage checks were also as required. Buildup No. 3 is currently available for operational testing under NASA Contract NAS 9-15831.

4.0 CONCLUSIONS

The conclusions reached during Phase V of this Technology Program can be summarized as follows:

- The scale-up capability of the solid polymer electrolyte technology has been confirmed by the demonstration of performance levels in 1.1 ft^2 cell hardware equivalent to those previously obtained in laboratory-size hardware.

- The solid polymer electrolyte fuel cell performance stability has been verified: laboratory-size cell NT (V)1-1 and full-scale unit Buildup No. 1 have demonstrated over 4300 and 3200 hours of operation, respectively, without any detectable loss in performances at 500 ASF load.

- All test evaluations at GE/DECP were and continue to be conducted utilizing commercial-grade reactants (i.e., 99.95% pure H_2 and 99.6% pure O_2). Since such reactants can have several ppm of carbon-bearing gases, the invarient performance demonstrated attests to the SPE fuel cell's tolerance to CO_2, CH_4 and CO at the levels commonly found in commercial-grade reactants.

- A determination of the useful life of the SPE fuel cell can be broken down into estimates regarding the life of the electrolyte, electrodes, and cell structures:

  - o The electrolyte life in the 5-mil configuration has been demonstrated in Buildup No. 1. The lack of any visual polymer degradation after >3400 hours, combined with the very low HF loss rate (<50 ppb in the product H_2O) over the test period, allows a projected polymer life in excess of 40,000 hours.

  - o Although the same electrode catalyst configuration has been on test for over 57,000 hours in Buildup AFC #6, the electrically conductive cathode wetproofing has been on test only a portion of that time. NT-03, with a 5-mil polymer electrolyte and electrically conductive wetproofing, has demonstrated over 11,000 hours of trouble-free, electrically-conductive cathode wetproofing. Since a means of assessing the rate of degradation

of this material is not available at this time, an estimate of total projected life must await the results of endurance testing.

- The sheet metal anode flow sheet (currently niobium) is the life-limiting component of the fuel cell stack. Demonstrated life is in the range of 5000 to 6000 hours using 3-mil stock, after which hydrogen embrittlement may result in crack failures. The 5-mil flow sheets of the scaled-up 1.1 ft^2 design have a projected useful life in excess of 10,000 hours. A useful life in excess of 10,000 hours will require demonstration and, if deemed necessary, design modification.

5.0 RECOMMENDATIONS

It is a recommendation of GE/DECP that the solid polymer electrolyte fuel cell be further developed in order to meet future space electrical power needs. The following paragraphs describe such a development program which is a logical extension of the work performed in Phase V.

5.1 Milestone Schedule

The following program plan describes the tasks to be accomplished in order to establish the readiness of the solid polymer electrolyte fuel cell technology for space shuttle power plant development qualification. A logical extension of the work performed under Phase V, the approach will be to design, fabricate and test-evaluate a 14 kW engineering model which represents, as closely as possible, fuel cell power plant (FCP) that could interface directly with the Space Shuttle vehicle as it is presently configured.

The characteristics of this FCP would be as described in Table II.

Completion of twelve tasks is required to demonstrate an engineering model, as shown in Figure 21. These tasks are costed separately, such that NASA may, if financial conditions warrant, fund the program on a task-by-task basis. It is expected that the original program can be accomplished within 18 months of the actual start of work.

5.2 Task Descriptions

Task 1.0 - Continued Development of Phase V Hardware

Further design refinement and subsequent demonstration will be accomplished under this task using the three sets of stack hardware and test facilities developed in Phase V of Contract NAS 9-15286. Among the objectives of this task will be:

- Extended endurance demonstration of multi-cell stack hardware.
- Integration and endurance demonstration of internal reactant humidification in multi-cell hardware.

TABLE II

PROPOSED FCP CHARACTERISTICS FOR SHUTTLE VEHICLE

Maximum continuous output	14.2 kW
Nominal minimum rating	4. kW
Voltage at maximum cont. rating	28.0 VDC
Current at maximum cont. rating	507 A
Efficiency at maximum cont. rating (incl. 200 W parasitic power*)	51%
Efficiency at minimum rating	53%
Voltage at minimum rating	32.2 VDC
Cell size (active area)	1.1 Ft.^{2} (1022 cm^2)
Number of cells	36
Size	14.3"x 14.3"x 24" (36.3 cm x 36.3 cm x 61cm
Dry Weight	135 pounds (61.2 kg)
Parasitic diffusion loss (incl. in efficiency calculations)	10 ASF (10.8 ma/cm^2)
Instantaneous peak short circuit current for .006 ohm short	1750 A
H_2 flow at maximum rating	1.5 Lb/Hr (.68 kg/Hr)
O_2 flow at maximum rating	12.3 Lb/Hr (5.58 kg/Hr)
Reactant pressures	85-90 psia
Condensate flow	13.8 Lb/Hr (6.26 kg/Hr)
Coolant flow	9.5 GPM
Coolant inlet temp.	180°F
Shutdown time	Instantaneous
Start up time	30 seconds
Est. production unit price	$170 K (1979 Dollars)

*Power required for coolant pump, controls, valve actuation, etc.

SPACE SHUTTLE ENGINEERING MODEL

Demonstrate an Engineering Model
Suitable for Retrofit into the Current
Space Shuttle Fuel Cell Interfaces.

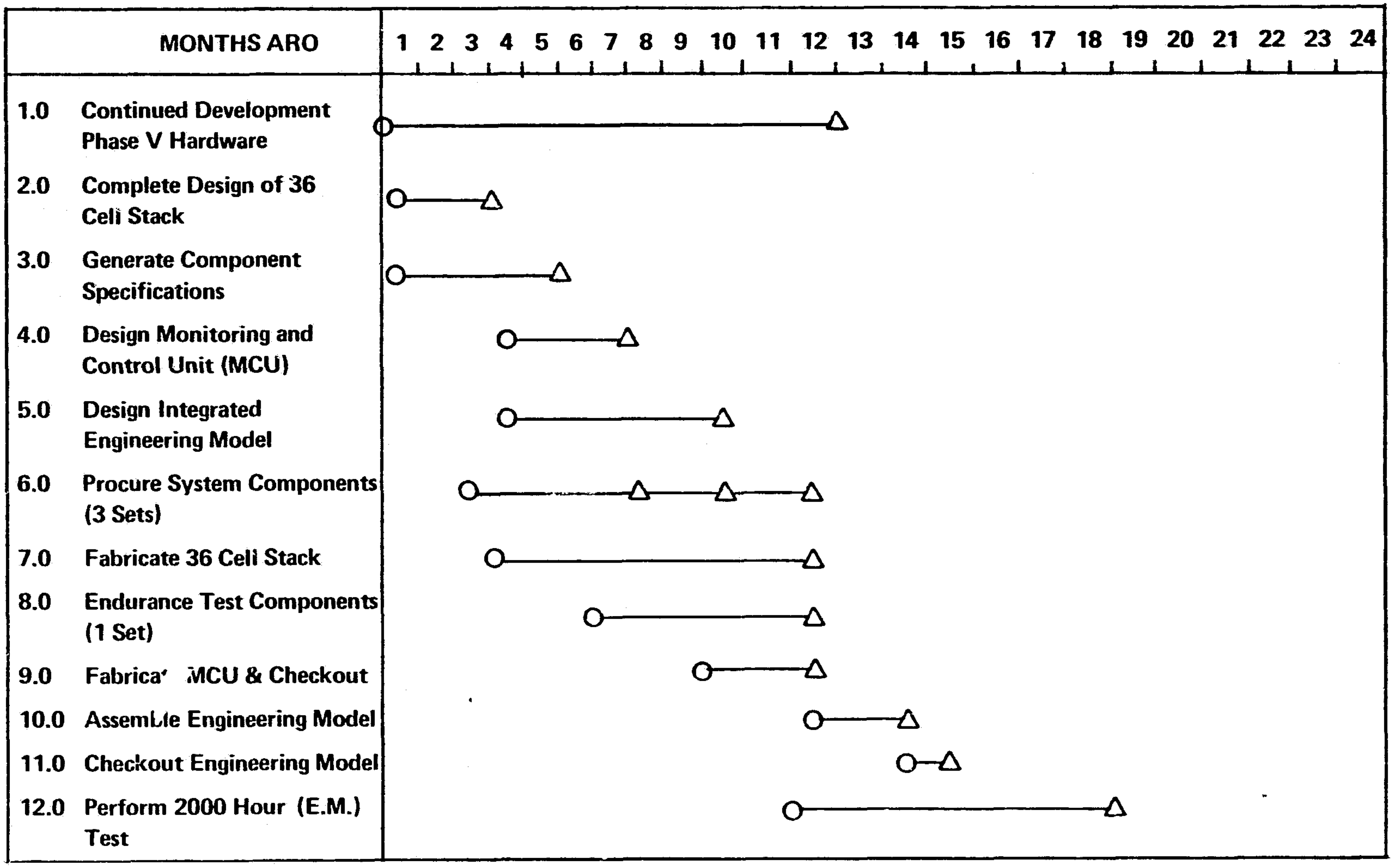

Figure 21. Program Milestone Schedule

- Design of a refined oxygen flow field for product water removal at lower parasitic power.

- Demonstration of higher-temperature operation (i.e., 220^{o}F coolant inlet temperature).

Task 2.0 - Complete Design of 36-Cell Stack (FCS)

The hardware designs established during Phase V will be modified and upgraded to provide a definition of the 14 kW fuel cell stack (FCS). Major among the design analyses to be performed, will be a reevaluation of the preferred location of the reactant humidifier fluid plate (i.e., central to the stack or as part of one end plate).

Task 3.0 - Generate Component Specifications

A specification will be generated for each of the fuel cell power plant auxiliary components, for the most part consisting of revisions to the existing specifications for auxiliary components generated during the NASA/JCS Space Shuttle Technology Program (NAS 9-12332), taking into account the specific interfaces as they exist in the Space Shuttle vehicle. However, changes that have evolved both in the fuel cell configuration and the SPE fuel cell packaging require that some new specifications be generated. These include:

- High-pressure reactant pressure regulators must be developed. The original Space Shuttle technology concept was to utilize propulsion-grade cryogenic reactants at low storage pressure. The oxygen reactant was to be fed, unregulated, directly to the FCP while the hydrogen reactant, also at low pressure, was to be regulated at 4 psi or more below the oxygen pressure. With the present Shuttle configuration, utilizing supercritical cryogenic reactant storage, high reactant pressures must be regulated down to FCP operational pressures.

- The development of electrically conductive wetproofing has enabled elimination of the wicking system for water removal and the pressure container for oxygen containment, producing significant advantages in both specific weight and efficiency. However, two new functions must now be performed in order to remove

product water from the operating FCP: First, the oxygen reactant must be circulated, such that the product water is dynamically carried from the stack in the zero gravity condition. Second, the liquid phase of the product water must be separated from the oxygen discharge stream.

- The circulation and separation functions may be performed in two independent devices, as described in the technical approach section, or there may be advantage to combining the functions into one device (i.e., a dynamic phase separator). This will be evaluated in this task. The technical approach also describes an electric motor-driven blower as the means of oxygen recirculation. Use of the energy in the high-pressure oxygen to drive the recirculator will also be considered as part of this task.

Task 4.0 - Design Monitoring and Control Unit (MCU)

The monitoring and control unit will be designed, utilizing the output of Task 3.0 ("Component Specifications"). This electric mechanical design will include such items as motor inverters, automatic control logic, and a means of removing generated heat in the space environment. The output of this task will be a set of electrical schematics and engineering drawings of the packaged monitoring and control unit.

Task 5.0 - Design Integrated Engineering Model (EM)

This task will utilize the outputs of Tasks 2.0, 3.0 and 4.0, as well as a detailed analysis of the existing Space Shuttle vehicle/fuel cell installation and operational interfaces, for the purpose of designing the integrated FCP. This design will include the FCS, the auxiliary components and the MCU. Integrating structures, wiring harnesses, etc. will also be part of this design effort. The task output will be a set of engineering drawings.

Task 6.0 - Procure System Components

It is presently envisioned that all the auxiliary components will be purchased items except for the MCU, which will be assembled in-house from purchased components (Task 9.0). The generated component specifications (Task 3.0) will be

submitted to established high-performance vendors for quotation. An attempt will be made to obtain at least three quotations for each component. Cost, delivery and previous performance will be factors utilized in the evaluation of the quotations. Orders for 3 sets of components will be placed, with the first set due in-house within 8 months of program start.

Task 7.0 - Fabricate 36-Cell Stack (FCS)

Raw material will be ordered for the engineering model of the 14 kW FCS. The cells and other stack components will be fabricated and assembled, utilizing the designs generated in Task 2.0. The assembled stack will undergo a series of non-operational tests including leakage (both internal and outboard) and flow checks and electrical resistance and shorting tests. Upon successful completion of these tests the FCS will be ready for integration with the auxiliary components to form the FCP.

Task 8.0 - Endurance Test, Components

Following acceptance tests of all components, one set of components will be selected for endurance testing. The purpose of this task will be to uncover any component design deficiencies before integration of the components with the FCS. Facilities will be prepared and the components will be subjected to operating conditions in simulation of those expected when part of the integrated FCP. The major emphasis of the endurance testing will be on the new types of components and those containing rotating parts. A goal of 2000 hours of successful simulation testing has been established for each component before integration with the FCS.

Task 9.0 - Fabricate and Check Out Monitoring and Control Unit (MCU)

High-reliability components will be procured and the monitoring and control unit subsequently assembled. Following the normal continuity and resistance checkout, functional tests of the assembly will be made. In many cases these tests may be conducted in conjunction with the simulated component endurance testing (Task 8.0). Following successful checkout, the MCU will be ready for integration with the FCS.

Task 10.0 - Assemble Engineering Model (EM)

This task consists of the actual integration of the

various FCP components which were all previously checked for suitability:

- Fuel Cell Stack (Task 7.0).
- Auxiliary Components (Task 8.0).
- Monitoring and Control Unit (Task 9.0).

Following the assembly, a confirmation of the FCP mass will be performed.

Task 11.0 - Check Out Engineering Model (EM)

The completed engineering model will undergo a series of checkout tests that will include:

- Leakage Tests.
- Flow Tests.
- Electrical Resistance Checks.
- Electrical Shorting Checks.
- Component Function Tests.

A formal checkout procedure and check-list will be generated to assure the appropriate sequence of checkout testing.

Task 12.0 - Perform 2000-Hour Engineering Model (EM) Test

The initial efforts in this task will involve preparation of the test facility and procedures. The test facility will be designed and fabricated with features that will allow unattended operation of the hardware (i.e., safe shutdown upon malfunction). Formal test procedures and check-lists will be generated to assure smooth operation of the hardware.

Following facility checkout, the 14 kW engineering model will be set up in the test facility and an integrated checkout performed.

The FCP will then be activated and operated through mission load profiles as determined appropriate by NASA/JSC. Testing to simulated mission profiles will continue with a goal of 2000 accumulated load hours.

APPENDIX A

COMPLEMENTARY RESEARCH AND DEVELOPMENT PROGRAMS

NASA/JSC FUEL CELL TECHNOLOGY PROGRAM

Complementary Research and Development Programs

There are research and development programs currently underway to GE/DECP which are related to the fuel cell technology development effort and which represent significant potential beneficial spin-offs to the NASA/JSC Fuel Cell Technology Program. Several of these efforts are funded through the IR and D Program or internal Future Benefit Programs, while others are funded through contracts with other Government agencies of industrial corporations. Summarized below are the most significant of these efforts currently in-process:

1. Evaluation of life capabilities of fuel cells operating on O_2/H_2 and air/H_2 in the 40,000 to 60,000-hour range. (GE IR&D)
2. Evaluation of the technology needed to run electrolysis cells for life at current densities in the range of 2,000 to 6,000 ASF. (GE IR&D)
3. Evaluation of cell life capabilities under conditions of increased operating temperature (240 to 300°F). (Industry)
4. Development of alternate cathode conductive wetproofing configurations with improved electrical and mechanical characteristics. (GE IR&D)
5. Development of lower catalyst loadings on both anode and cathode to reduce material costs by a factor of 6 to 8. (Industry)
6. Scale-up of manufacturing capabilities and evaluation of process flow and equipment development needed to reduce labor involved in fabrication of membrane and electrode assemblies by a factor of 2 to 3. (GE/DECP)
7. Improve platinum plating procedures employed on current collectors to reduce high contact resistances associated with long-life capabilities. (GE IR&D)
8. Evaluation of starting and stopping procedures for fuel cells utilizing gas switching techniques. Start-up in a few milli-seconds is the goal. (GE IR&D)
9. Evaluation of alternative high-stress frame materials to develop a more effective cell sealing capability. (GE IR&D)
10. Development of a cell failure isolation device. A significant cost impact results when requiring the replacement of only one cell of a multi cell stack in the event of a cell cross-leak. (GE IR&D)